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Daylight control and performance in office buildings using a novel ceramic louvre system

R. Urbano Gutiérrez[a,*], J. Du[a,b], N. Ferreira[a], A. Ferrero[c], S. Sharples[a]

[a] School of Architecture, University of Liverpool, Liverpool, UK
[b] School of the Built Environment, Liverpool John Moores University, Liverpool, UK
[c] Instituto de Óptica, CSIC, Madrid, Spain

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ABSTRACT

This study examined the design and daylight performance of a new louvre screen for office buildings. The screen was evaluated for three different material finishes: specular aluminium as a traditional material commonly used in louvres, and two types of ceramic finishes, with the intention to reduce the systems' environmental impact. The new system was assessed taking an unshaded window, a window with a rod screen and a window with venetian blinds as references. Annual performance simulations for a full-scale room, using the lighting software Daysim, were conducted to assess the effect of the three material systems on indoor daylighting levels and distributions using both the traditional Daylight Factor and climate-based daylighting metrics (Daylight Autonomy DA and Useful Daylight Illuminance UDI). The results show that the proposed louvre system can provide satisfactory daylight levels and visual comfort within the room, while ceramics appear as a promising alternative material to be used in the production of advanced daylighting technologies.

1. Introduction

Buildings in industrialised countries are responsible for 40% of our total energy consumption. Heating, cooling and lighting are the three largest uses of energy in buildings. For commercial buildings 73.4% of that energy is electric consumption, of which 11% is for artificial lighting, while heating and cooling account for 34% [1,2]. Most of the electricity supplied to lighting systems is still produced from burning fossil fuels (50%) [3]; likewise, 84% of heating and cooling is still generated from fossil fuels [4]. Despite the fast and encouraging improvements in recent years in lighting technology, the production of light is still an inefficient process, which is particularly relevant for energy use in commercial buildings [5]. In addition to environmental and economic factors, the effective use of daylight also contributes to wellbeing and increased work environment satisfaction for occupants. The optimisation of window systems to improve daylighting distribution in buildings to reduce electric lighting usage, in combination with the optimisation of the system's thermal performance, has been estimated to save around 9% of the energy consumed by buildings [6]. Therefore, the investigation of façade systems that can deliver improvements in both types of performance plays a critical role in the current quest to achieve zero-carbon buildings and energy reduction targets set by governments.

Windows still present the most common strategy for daylight provision in both existing and new commercial buildings. Unprotected windows produce glare and irregular daylight distribution patterns in an interior, which might create areas of excessive brightness in the perimeter of the building (light usually reaches up to one to two times the height of the window wall). In contrast, in the core of the building spaces may be poorly lit naturally and will require artificial lighting. To generate visually comfortable luminous interiors, the building's facade opening should integrate a daylighting system that will try to distribute sunlight and daylight more evenly across the room's working plane. By enhancing the distribution of natural light, the need for electric lighting will be significantly reduced.

Within the range of daylighting technologies, reflective light-redirecting technologies are designed to stop direct sunlight falling on to building occupants and, instead, be redirected onto the ceiling to use as a source to diffuse light. This will improve the penetration and distribution of light deep within the space. In this study, a new light-redirecting technology is proposed that is based on a horizontal louvre system manufactured from ceramic materials. The main goal was to investigate the potential lighting performance of this louvre system by exploring different geometries in the louvre's profile. The first part of this paper focuses on the daylighting performance of the proposed louvre system. It introduces its design and operation based on

* Corresponding author. Liverpool School of Architecture, Leverhulme Building, Abercromby Square, L69 3BX, Liverpool, United Kingdom.
E-mail address: rug@liverpool.ac.uk (R. Urbano Gutiérrez).

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preliminary test results from computer simulations, with the intention to provide a proof-of-concept for the new daylighting system. The second part of this paper centres on the investigation of alternative material configurations for the new louvre system. Specifically, it assesses the use of ceramic materials, which have been chosen because such materials have a much smaller environmental impact and are less energy-intensive than the traditional material used in louvres, such as aluminium and plastics.

Most of the processes and resources used in the building construction industry exert a significant impact on the natural environment [7–10]. This is particularly true for the materials used to fabricate buildings and the systems used to control the environment within those buildings, such as façade elements [11]. Consequently, it is important to examine the potential of alternative building and systems materials that have a lower environmental impact, are less energy intensive to manufacture and which are readily recyclable. Ceramic materials are a promising option since they are abundant, easily available, and are often used in their natural state with very little processing before firing. The embodied energy of a building material can be described as the total energy associated with the production and use of that material. The embodied energy of baked clay is approximately 3 MJ/kg, the embodied energy of a simple ceramic tile is around 6.5 MJ per tile, and for a standard extruded brick is about 6.9 MJ per brick (standard weight being 2.3 kg per brick). In contrast, aluminium, a typical material used in the production of façade technologies, has an embodied energy of the order of 218 MJ/kg. In terms of the unit carbon dioxide equivalent (CO2e) baked clay is 0.24 kg CO2e/kg or 0.55 kgCO2 per brick), while for aluminium the value is 12.79 kg CO2e/kg [12]. Furthermore, ceramics is a very durable material, which ages in an aesthetically pleasing way and which can cope with environmental changes over very long periods of time. In terms of structural and aesthetic potential, ceramics have high compressive strength and are very plastic in form. These are properties that can be explored further in combination with digital fabrication technologies, such as 3D printing [13–16]. This means that highly complex, non-conventional forms can be created in ceramic that would have been impossible to achieve in the past.

Despite these developments and potential benefits, the use and performance of ceramics in contemporary facades has received limited exploration in environmental research areas such as sunlight control and daylight performance. In recent years, examples of ceramic brise-soleil systems have been designed and implemented in some renowned office buildings. For example, Renzo Piano's New York Times Building (completed in 2007) positioned narrow horizontal ceramic tubes, held in a steel frame, 500 mm in front of the fully glazed glass envelope [17]. The same architect's Central Saint Giles building in London, completed in 2010, has façades consisting of panels covered, in total, by 134,000 brightly coloured, prefabricated glazed terracotta pieces [18]. The Sony Research and Development Centre in Tokyo was designed by the Nikken Sikkei Research Institute and completed in 2011. Its eastern façade uses a system called BIOSKIN which cools the exterior of the building by channelling rainwater collected from the roof through porous ceramic pipes. As the water evaporates from the pipes the adjacent air is cooled by up to 2 °C. In addition to natural cooling effects, the BIOSKIN screens also cut out direct sunlight, thereby reducing air-conditioning loads [19]. In these screens the ceramic element usually takes the form of a rod or ‘baguette’. In terms of daylight control these ceramic rods only perform as shading devices, by just blocking part of the incident sunlight.

The main goal of this study was to investigate the potential lighting performance of ceramics when used in light-deflecting louvre technology by exploring different material finishes. For this purpose, this paper analyses the daylighting performance of the new louvre system for two different ceramic finishes on an annual basis. The ultimate intention was to test if two benefits can be brought together in one façade technology: optimised daylighting performance in combination with the use of a low environmental impact material. The potential thermal benefits of the louvre system, such as providing thermal mass or a protective casing in which to house phase change materials as it has been studied in recent studies using polycarbonate and glass materials [20–23], are not considered in this paper, but will form the basis of further work by the authors.

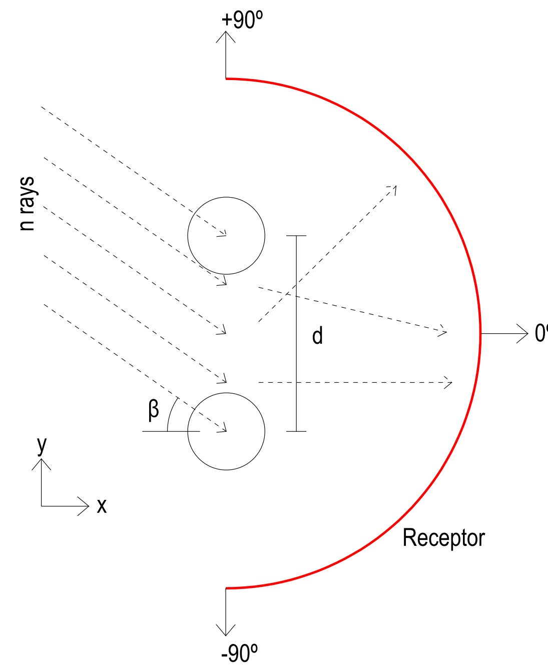


Fig. 1. Ray-tracing basic simulation setup: distribution of n light rays around two cylindrical louvre sections spaced apart by a distance d. For different elevation angles, the scattering properties of the louvre system was evaluated over a semi-circular receptor.

2. Daylight performance of louvre systems

Daylighting systems can be divided into different categories, according to three main criteria: daylighting function (light distribution performance, visual comfort, and solar gains control); building integration (in the exterior of the building, in the interior of the building, or within the envelope); and type of operation (passive or active). Each possibility presents different characteristics that need to be taken into consideration when designing a louvre system.

Horizontal louvres are effective when the sun is high in the sky. They can be designed to let the winter sun in, block entry of the hot summer sun, and restrict the view of the exterior bright sky [24]. If the sunlit surfaces of the louvres are viewed from the interior, they might cause visual discomfort because of their excessive brightness. Diffusing or scattering the light after its redirection would mitigate that glare effect (from both the sky and the daylighting system) and would avoid the sharp-banded light pattern provided by mirrored louvres [25].

Exterior louvres have to be robust enough as to withstand wind loads and exposure to the elements, and avoid uncontrolled movement and noise. This makes the system bulkier and more expensive than internal systems. Operation (if moveable elements), maintenance, and cleaning of louvres can be difficult, especially when they have highly reflective coatings. When blocking the solar gains and providing coolness are the main goals, the best position to place the shading device is outside the building [26]. Leaving an air gap between the sunshade and the window (at the top) so as not to trap hot air, perforating the sunshade to allow self-ventilation, and using a low emissivity material, are key design aspects in order to optimise the sunshade's heat-control performance. Concerning daylighting efficiency, external louvres catch more light, as no other façade element will shade them.

Interior louvres are more accessible to allow mobility, maintenance,

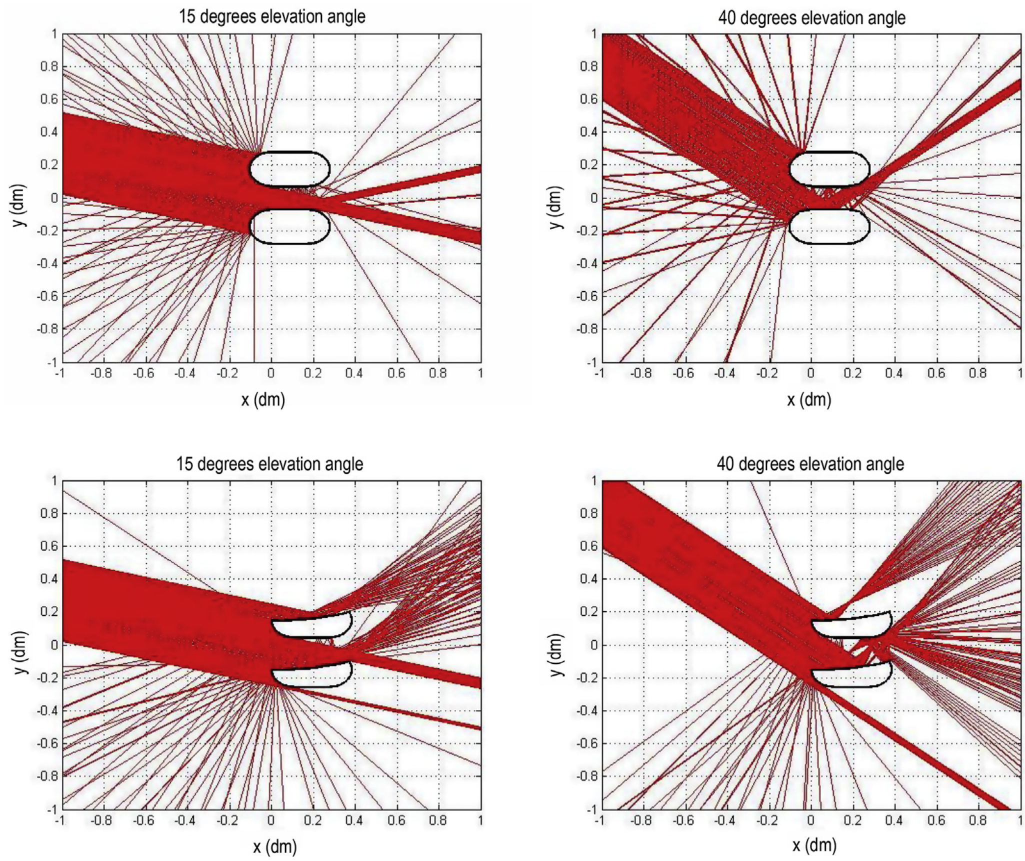


Fig. 2. Comparison of the ray tracing patterns of two consecutive elements of a standard ceramic rod screen and two consecutive rods with the modified top part.

and cleaning, and can be smaller, requiring less structure and cost. Inside the building is the best position when providing thermal mass and solar gains is the main goal [24]. When direct radiation hits the louvres, they will absorb some heat, which will be radiated and convected to the inside of the room. If the goal is to reduce secondary solar gains produced from the internal screen, then the screen has to be made of a very reflective material, so the impinging sunlight would be mostly reflected and only a minor part would be absorbed. The directly reflected light would go back to the outside, for which the glazing should be of high transmittance and lacking any filters to avoid any obstacles in that process. Internal louvres catch less sunlight, as the window reveal, and/or other façade components, will partly shade them. In many contemporary facades, louvres are installed in between glass panes, since this option combines the advantages of the other two and mitigates their disadvantages. Moveable louvres can be adjusted (raised, lowered, and tilted to different positions) to changing sky conditions and user needs in response to sun, sky brightness, and view control. This flexibility demands more maintenance and a complex automated system (if computer-based) or, alternatively, responsible users with some understanding of energy efficiency [27]. Generally, passive systems are less expensive, in both upfront and maintenance costs, but due to being fixed, they are typically only effective for a limited range of sun and sky conditions. Attention has to be paid to their design to impede uncontrolled direct sun passing through.

There has been extensive research on horizontal reflective louvres, giving rise to a variety of systems. These systems usually consist of a vertical array of slats, whose profile is defined so that daylight is reflected up onto the ceiling. The search for the optimised slat profile lies in achieving the desired light distribution for as many as possible sky conditions, while preventing glare, managing heat, and allowing views [26,28–31]. The availability of new daylight modelling tools has enabled the evaluation of some of these systems on an annual basis [32], providing more reliable information about these systems' performance. Despite these advances in daylighting technology, the existing systems still suffer from several drawbacks. At times of the day and year they can let uncontrolled sunlight in, reject too much daylight, allow light to exit at a downward angle that might produce glare, or reflect light at too high of an angle to provide an efficient light penetration depth. Another issue is that when the louvre screen is designed as a fixed system it presents limitations in admitting incoming light [33,34]. The uncontrolled penetration of solar radiation is particularly critical in very sunny climates where issues of overheating in the summer and glare are crucial.

3. Louvre design

3.1. Performance objectives

The objective of the first part of this research was to design a louvre system that could deliver daylight and thermal control performance as part of an environmental façade strategy for office buildings. An office space was modelled and located in Madrid, which was chosen as having sun/sky conditions that could potentially be used successfully for daylighting if solar gain and daylight distribution could be controlled. The following design conditions were set, considering both optimised performance and standard contemporary constraints for office spaces, in which the system must respond to prevailing climatic and contextual characteristics.

According to several findings [35–40] a louvre with specular surface has been proved as a daylighting system that could achieve the optimal daylight performance, especially under a highly luminous sky with sun, as it is mostly the case in Madrid. The average total sunshine hours in Madrid is 2769 h per year. This is one of the largest totals of sunshine duration hours in Europe. Equally, Madrid enjoys one of the best

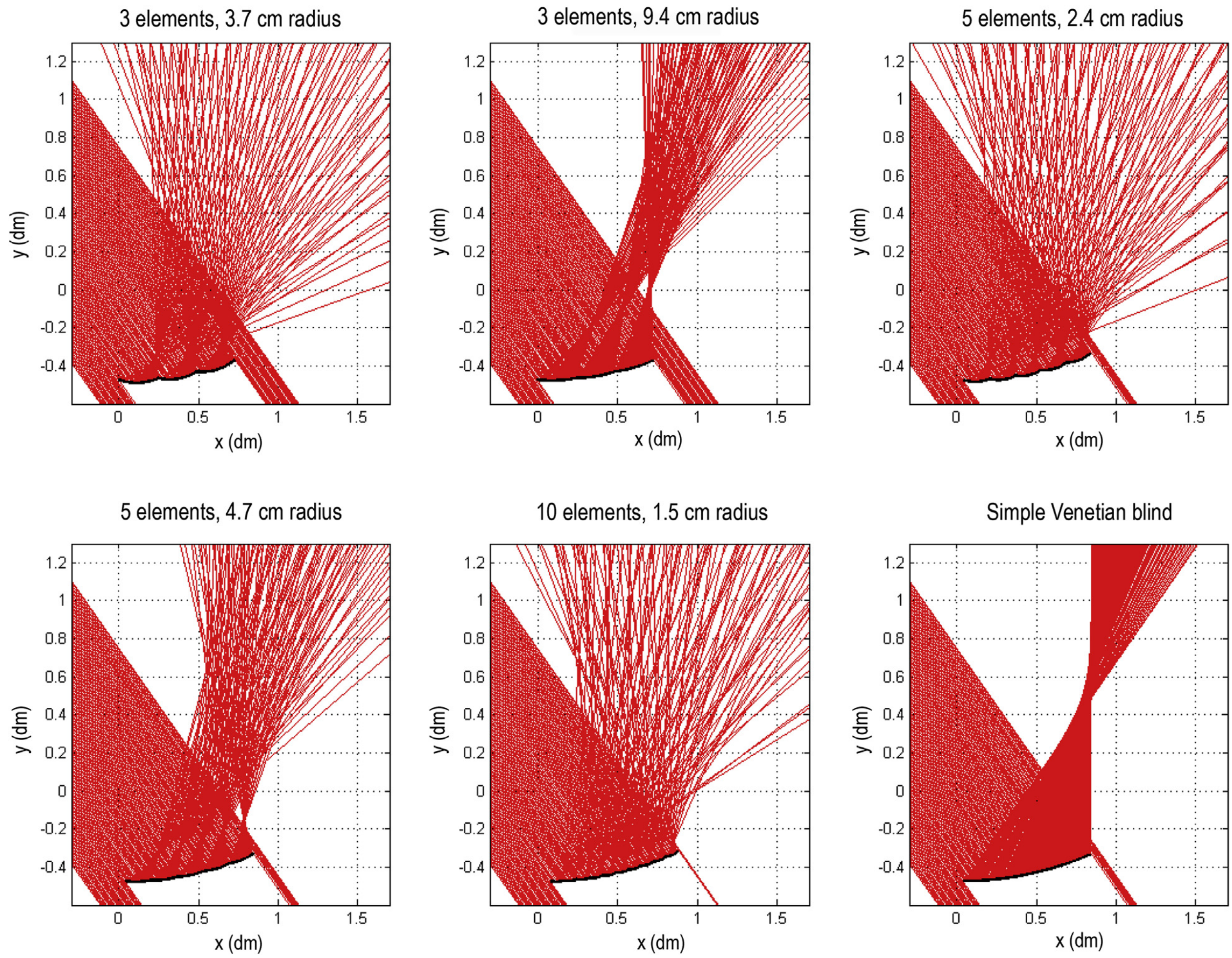


Fig. 3. Ray tracing through some of the tested louvre's topsides for an elevation angle of 50°, including a simple Venetian blind.

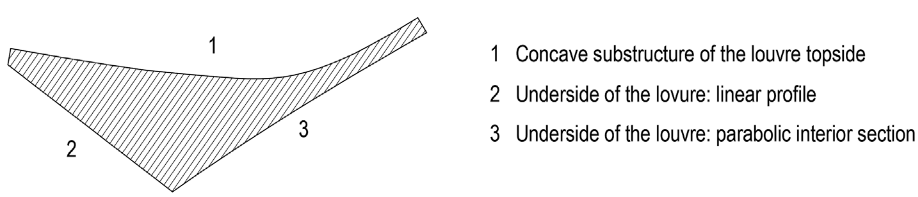


Fig. 4. Description of the three sides of the louvre's profile.

number of hours of daylight in Europe (ranging from 10 h per day in December to 15 h per day in June) [41]. Thus, it was clear that highly reflective louvres would be an efficient light-controlling system in this location, providing a valid baseline for this study's assessment. The studied system and office arrangement modelled in the study had the following requirements and features:

- Lighting: the system must redirect sunlight and skylight in order to have a good distribution of light in the room and increase illuminance levels for both clear and overcast skies throughout the day and year.
- The system must combine the redirection and scattering of light to avoid the typical venetian blind pattern. Important aims included the minimisation of the cut-off angle and the provision of views.
- Office space: lighting simulations were run to get illuminance results for a generic building room (3 m wide x 9 m deep x 2.7 m high) with side lit vertical glazing only. The space was deliberately set to be very deep at 9 m.
- The whole south-facing front of the room was considered to be window (3 m wide x 2.7 m high), with the louvres installed either outside or inside the window, and a spectrally selective glazing was chosen so that solar heat gains were minimised.
- Urban surroundings: it was assumed that there were no obstructed sky views, even in the lower portions of the sky.

3.2. Generation of the ceramic profile

To accommodate both functions (i.e. daylight and thermal control performance) the louvre needed to present a profile that incorporated a cavity, intended to be used to contain either phase change materials (for thermal mass) or water (for evaporative cooling), which was set as a requirement in the louvre's design. A lighting analysis ray-tracing algorithm developed with MATLAB was implemented to define the profile of the ceramic louvre by estimating its lighting behaviour. The problem was idealised as a two-dimensional light propagation scenario, where only the cross-section of the ceramic louvre was considered. The ray-tracing algorithm was then used as an assessment tool when carrying out the parametric optimisation of the louvre's geometry, which was a thorough process assessing different families of geometries. The louvre was considered to present a highly reflective surface. In this

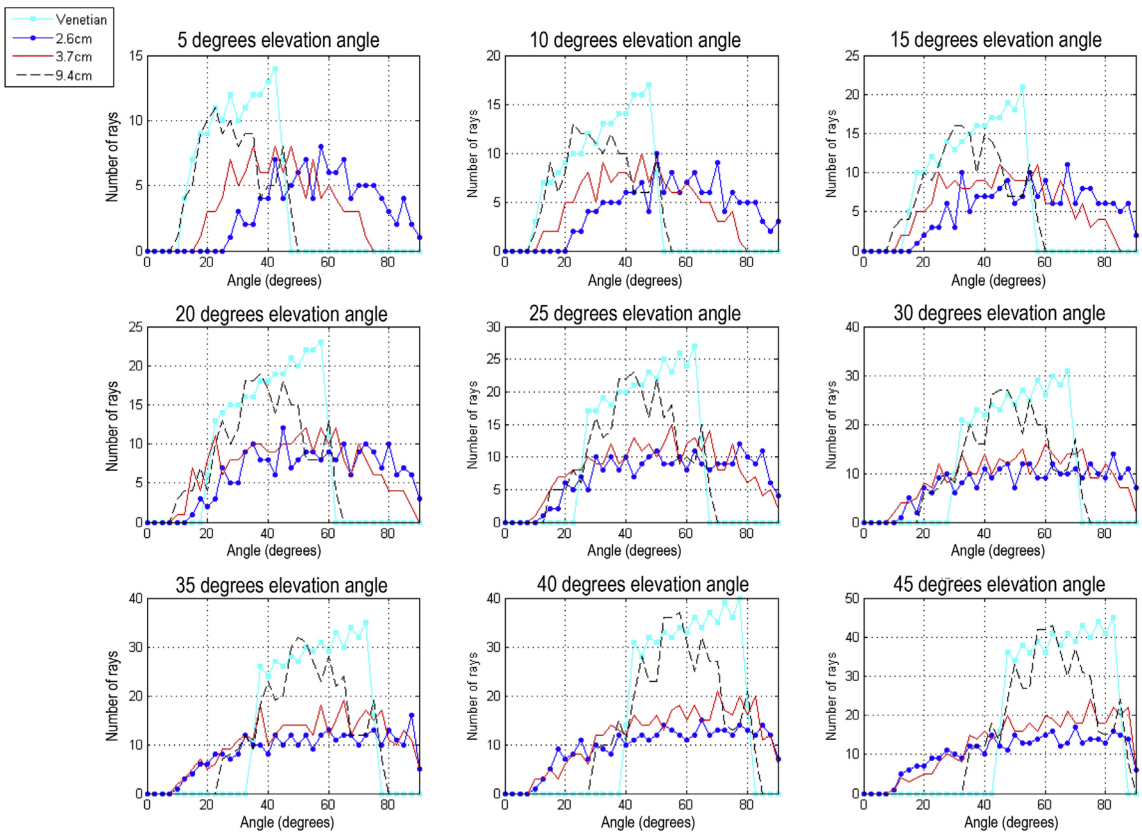


Fig. 5. Angular distribution of the transmitted luminous flux for different elevation angles.

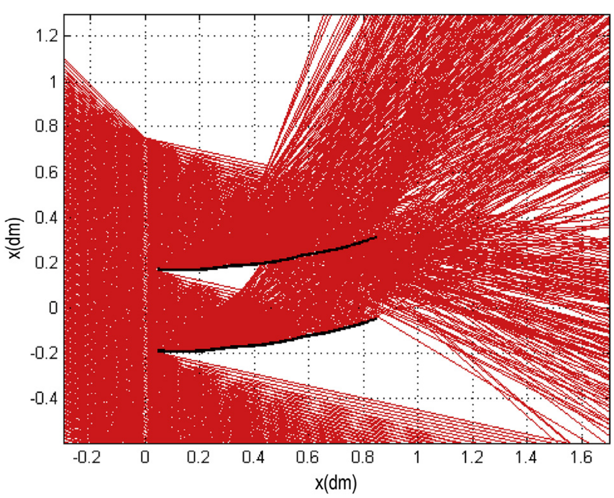


Fig. 6. Performance of the louvre's topside when superimposing the ray tracing patterns of two consecutive louvres composed of three elements with a radius of 9.4 cm for elevation angles between 15° and 50°.

preliminary study, all the reflections were specular; there was no scattering component in these calculations.

The algorithm is defined according to the following lighting targets: block sunlight in the summer; allow sunlight to pass through in the winter; distribute light throughout the room in order to avoid glare (including scattering properties); allow the exterior to be seen from inside the room (exterior visibility, defined by distance between louvres, louvre shape and louvre rotation); and there must be a restriction in the maximum possible diameter of the louvre and distance between sections of the louvre system, so that all louvres in the system are able to complete a 360° rotation for lighting adjustment. The simulation assesses the number of light rays (n), incident from a variable elevation angle (θ) on two louvre sections separated by a distance (d), that cross the louvre system and hit a receptor line placed behind (Fig. 1).

Other variable parameters include: density of light rays; generation of geometries (line and curvilinear segments; radius and maximum possible outer radius; distance between louvres; angle of aperture; x, y, z dimensions; boundaries; light ray source; surface properties; reflections and receptor definition. The design is further optimised using a Genetic Algorithm (GA), whose basic steps are: generate the genes of each individual and the corresponding geometry; evaluate lighting performance of each louvre design generated; select the geometries with the best performances; generate the offspring from the best geometries (crossover and mutation); and go back to the second step until satisfactory geometry is obtained. GA parameters used: size of population (200), number of generations (60) and mutation rate (1%). This was a long progressive process where the best response in the analysed parameters led to the selected geometry.

All the louvres sections were assessed for Madrid (40°N latitude) at 12.00 noon, with the louvres facing south. Slight alteration of the optimised profile would be necessary to tailor the design for other latitudes. The winter season was assumed to be between the autumn and spring equinox (22nd September and 20th March), and the summer season was assumed to lie between 20th March and the 22nd September. The solar altitude at solar noon is 50° for the days corresponding to the spring and autumn equinoxes, and 27° and 73° for the winter and summer solstices respectively. During summer days at solar noon the angle of the sunrays with the horizontal plane will lie in the interval [50°, 73°] and in the winter it will lie in the interval [27°, 50°]. The lighting performance of each louvre's geometry was assessed in the range 15°–50°, using 5° intervals. The designs were produced to take advantage of the high intensity of direct sunlight (four to seven times greater than diffuse skylight), given that diffuse daylight from the sky

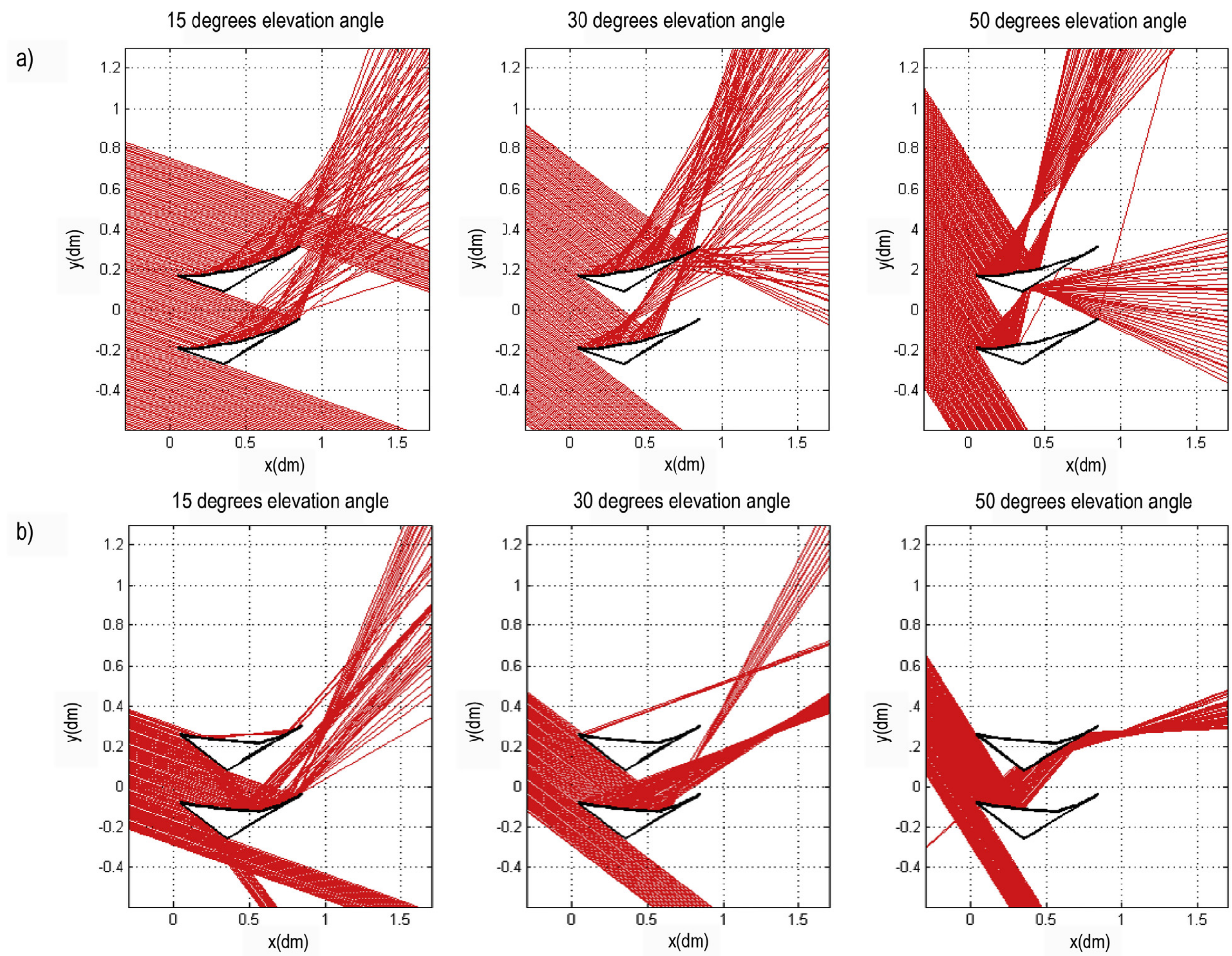


Fig. 7. a) Ray tracing of the complete louvre for incoming elevation angles of 15°, 30° and 50°; b) ray tracing of the modified louvre for incoming elevation angles of 15°, 30° and 50°.

and surroundings contributes insignificant daylight illuminance due to its lower intensity [38].

3.2.1. Upper part of the ceramic louvre

The standard rod screen implemented in many buildings was an appropriate starting point to design the new hollow profile for this investigation. However, preliminary results obtained, using the GA approach, confirmed that using horizontal shapes (smaller dimension in Y axis), allows for a much higher visibility to the exterior than more vertical shapes (greater dimension in Y axis), while scattering the same amount of light, and concave shapes on the upper surface of the louvre gave a better performance than the more common cylindrical or flat shapes, according to the set targets. Indeed, the concave curved upper surface collected as much light as possible in the required seasons and created a distribution light pattern that presented a clear redirection of the light upwards while maximising the angle of scattered light. As anticipated, the standard rods used in many current brise-soleil systems proved less efficient than an equivalent profile with a flatter, more curved top surface (Fig. 2).

The next step was to study the lighting scattering patterns of different circular sections, experimenting with different curvatures and tilted positions (Fig. 3). To obtain a more complete pattern (including a wider range of scattered light directed towards the ceiling of the room), the best curve was chosen as a base trajectory over which a composition of the best curved segments obtained in several numerical tests were implemented. This was called the concave substructure of the louvre's top side (Fig. 4). Again, different concave substructures built with different numbers of circular elements were studied and the most effective combinations identified.

As the curvature of the concave curves in the substructure elements increased (the radius decreased), the scattering pattern became more diffused, i.e. the reflections occurred over a wider range of angles. However, a significant part of the direct sunlight was being reflected back to the exterior. This could be an important disadvantage of this design if care was not taken when designing the remaining body of the louvre. If the curvature of the substructure elements was decreased (larger radius), then the scatter diagrams obtained were still more diffuse than the ones obtained for a single element of the conventional Venetian blind. Furthermore, nearly all the incident sunlight gets directed towards the inside of the room, especially when three elements were used together with a radius of 94 mm (Fig. 5).

3.2.2. Bottom part of the ceramic louvre

When superimposing the ray-tracing patterns of two consecutive louvres composed of three elements, using a radius of 9.4 cm for different elevation angles, there was a remaining blank triangular area underneath the first outer section of the louvre, which did not affect the light performance. That area can therefore become solid without interfering with the ingress of light, leading to the definition of the first section of the underside of the louver as a linear profile (Fig. 6).

The interior section of the bottom part of the louvre was made parabolic to redirect most of the incident light upwards towards the interior of the room. Looking at the light patterns of the second section of the louver (the internal lower side of it), it became clear that there

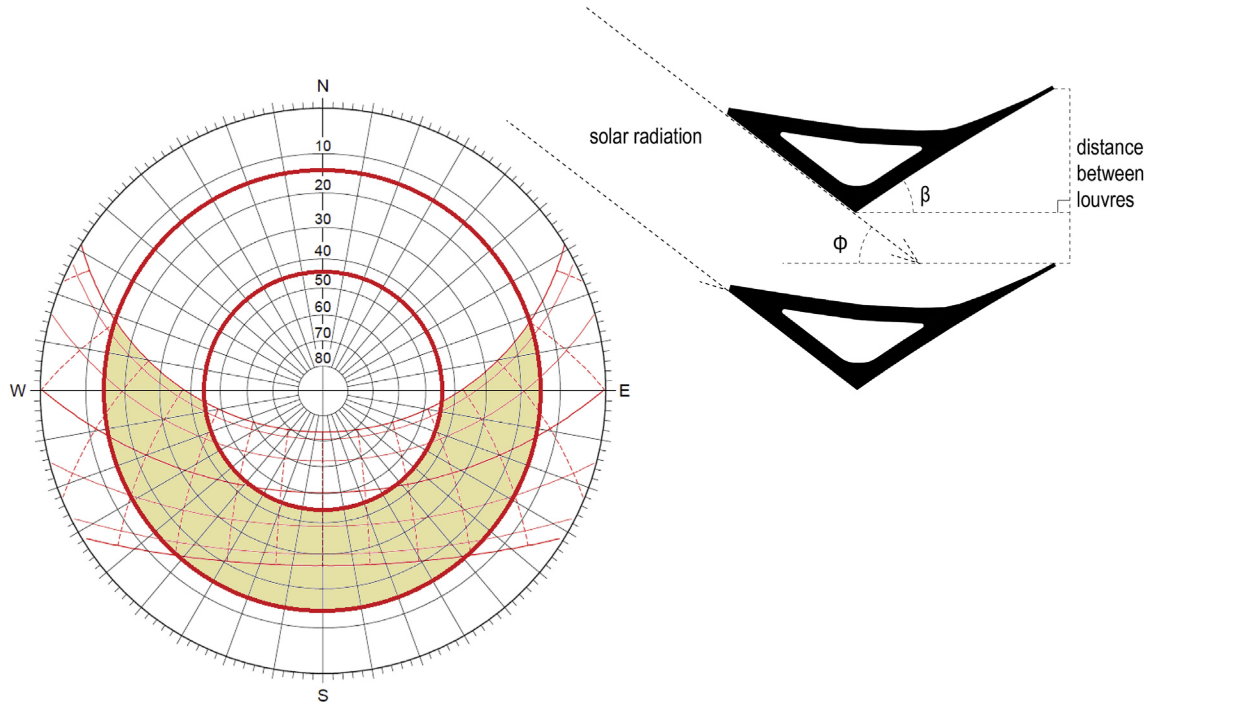


Fig. 8. Cut off angles for the louvre system (in section, top right) and sun-path diagram for 40° N indicating the louvres cut off angle: for elevation angles below 15° and elevation angles higher than 45°, the louvre system will not be able to efficiently redirect all incoming light (bold circles at 15° and 45°). The shaded area indicates the range of light angles that the system can efficiently redirect.

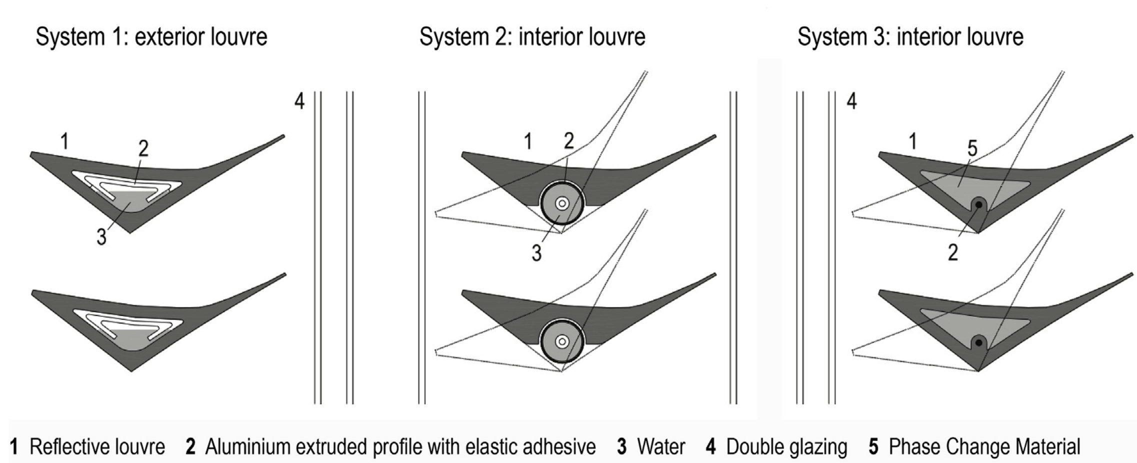


Fig. 9. Three potential adaptations of the louvre profile to become a window component with a designed thermal performance.

was a region of the louver from which light was having an undesired performance when it entered at an elevation angle of 50° (Fig. 7 a). That light was redirected to a region of the lower side of the upper louvre that would send that light downwards, i.e. the region after the peak of the triangular shape. A further modification of the louver profile considered two options to mitigate this problem. One involved extending the bottom first straight section of the louvre to block that small region of light that went downwards, but that would mean losing the light entering at noon during the equinoxes. The other option considered lifting the first upper section of the louver to reflect the incoming light deeper towards the internal lower section of the above louver, trying to avoid the region after the triangle's peak. This second option provided a more efficient performance in which more light was controlled although for elevation angles higher than 45° an increasing part of the incoming light was starting to get rejected. A further modification was carried out to minimise the amount of light that was reflected back, which consisted of replacing the first two circular sections of the top part of the louvre by a single parabolic section (Fig. 7b).

3.3. Final louvre description

The proposed screen was a horizontal array of identical reflective louvres, which redirected incoming light in a controlled manner deep into the office space. The resulting performance was scale independent and did not represent any particular size of the louvre profiles, as long as the cross-section relative dimensions remain the same. Light redirected from the louvres was always at an angle above horizontal, regardless of the incoming direction of the light. Most of the light exited the louver at angles between 0° and 45°. By observing all the ray paths described by incoming rays at different positions and elevation angles, it could be noticed that all of them were deflected by the louvres, and none of them exited at an angle lower than 0° above horizontal. The cut

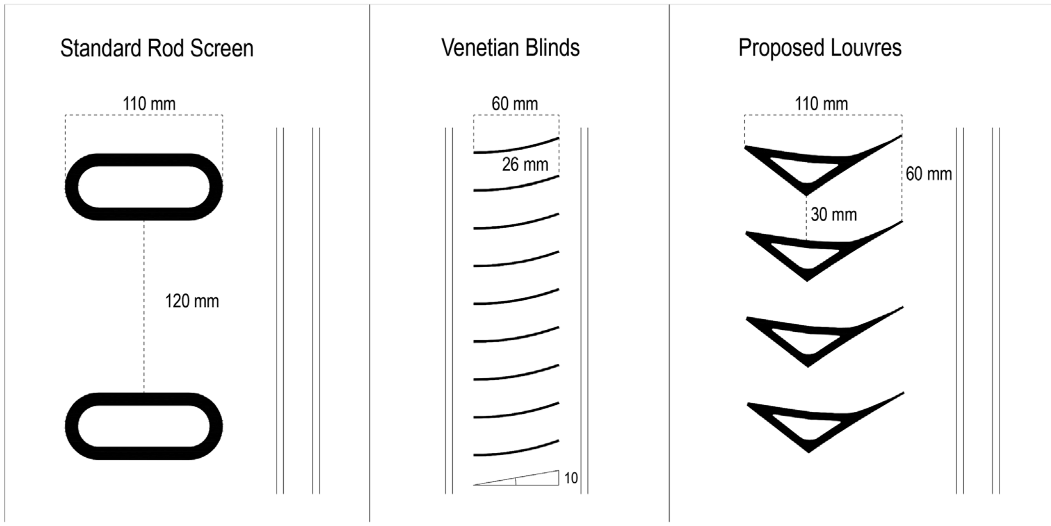


Fig. 10. Sections of reference systems, rod screen (left) and venetian blinds (centre) in relation to the proposed louvres (right).

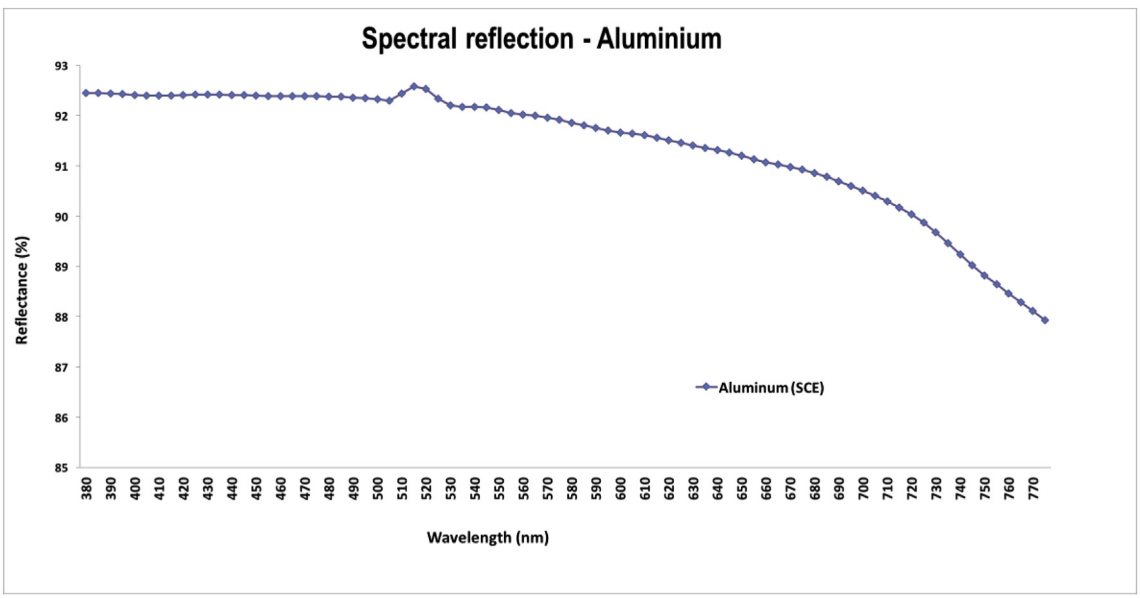


Fig. 11. Spectral reflective properties of polished aluminium as a function of wavelength.

Table 1
Room and material surface photometric properties.

Room Surface Photometric Properties	Reflectance/Transmittance
Wall	0.6 (grey, diffuse)
Ceiling	0.8 (white, diffuse)
Floor	0.3 (grey, diffuse)
Window	0.64 (double panes, transmittance), 0.8 (single pane, transmittance)
Shading Material Photometric Properties	**Overall Reflectance & Materials**
Rod	0.92 (specular, polished aluminium)
New louvre (exterior)	0.92 (specular, polished aluminium)
New louvre (interior)	0.92 (specular, polished aluminium)
Venetian Blind	0.92 (specular, polished aluminium)

off elevation angle ranged between 15° (for light normal to the façade in azimuth) and 0° (for light nearly parallel to the façade in azimuth). Light was also partially or completely blocked for elevation angles above 45°. The cut off angle is defined as the precise angle at which direct solar radiation is prevented. It is a function of louvre geometry and the solar angle, so that direct solar radiation, when present, it is either blocked or redirected by the louvre system. The desired louvre profile and the angle at which is positioned in the system (β) was designed to use as much of the incoming light as possible, and reduce the cut-off range of angles. In the optimised louvre design, the useful range of angles therefore go from 15° to 45°, which means that the louvres will effectively redirect the majority of the annual impinging sun light (except for absorption losses) (Fig. 8). Although for simulation purposes the optimised louvre was used as described above (just using the louvre's outline), as a component of a window system that also includes the previously described thermal performance within realistic window units, the louvre profile would need some adaptation. A basic description of these potential adaptions can be seen in Fig. 9, in which we can see the louvre system as part of a double glass façade in three different positions (exterior, in the cavity between glass layers, and interior), as well as showing preliminary design possibilities to contain water (Systems 1 and 2) or PCMs (System 3).

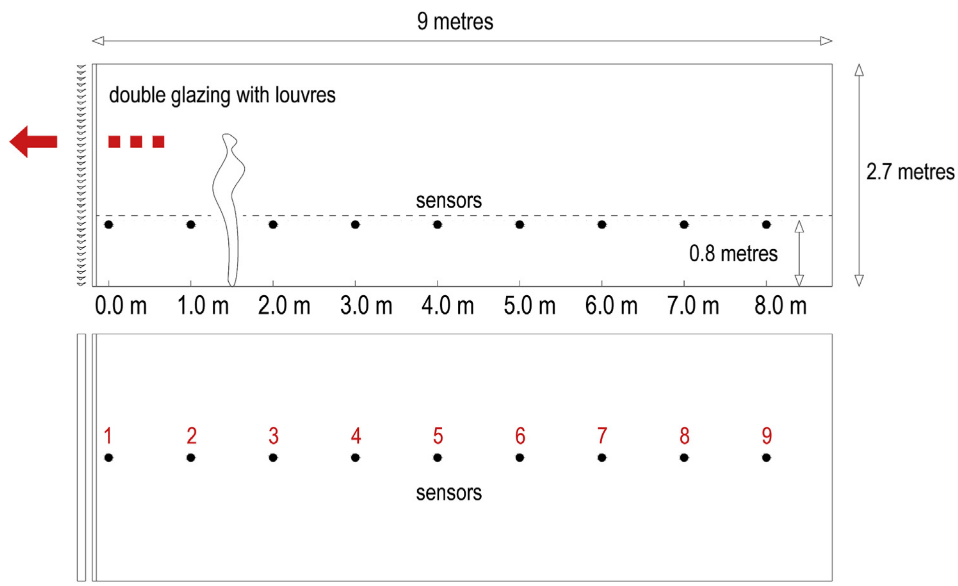


Fig. 12. Floor plan (bottom) and section (top) of the model room, showing the position of the nine sensors, spaced apart 1 m.

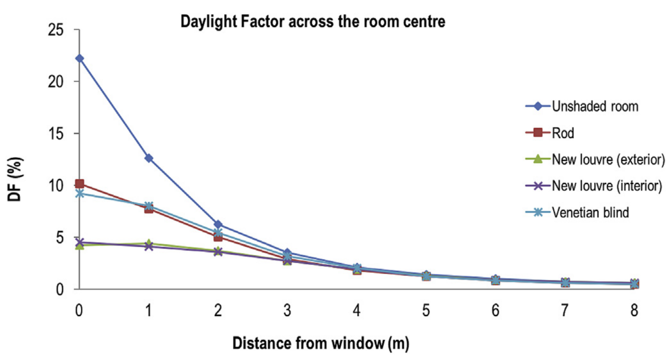


Fig. 13. Daylight Factor (DF) results for all compared systems.

4. Daylighting performance analysis

4.1. Simulation settings

In the generic office room (3 m wide × 9 m deep × 2.7 m high), the daylighting performance of the new louvre was investigated using computer modelling. Several architectural features were considered for these simulations. First, this study included three different orientations: south, southeast and southwest. Second, the new louvre was compared to three window situations: the room with an unshaded window, the room with standard rod screens (as the current most extended hollow-profile screen solution for windows), and the room with standard venetian blinds installed in the window (as the most commonly used solar-control solution) in sunny locations as Madrid, as described in Fig. 10.

The whole south-facing front of the room was considered to be window (3 m wide by 2.7 m high) with the louvres installed either externally or internally. The rest of the walls and the ceiling were modelled as completely opaque, with a diffuse grey or white finish respectively. Both the new louvre and the reference case studies were modelled using polished aluminium, a metal material commonly found in buildings. Its spectral reflectance [380 nm–770 nm] were taken from two recognised sources [42,43], as shown in Fig. 11. Table 1 gives the photometric properties of the room surfaces and shading materials.

To provide a quantitative idea of how the different systems performed over a year, daylight computer modelling was carried out using the daylighting software Daysim [44] to calculate Daylight Factor (DF) [45] as well as the two dynamic daylight performance metrics Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) [46,47]. Daylight factor (DF) is a daylight availability metric that expresses as a percentage '*the amount of daylight available inside a room (on a work plane) compared to the amount of unobstructed daylight available outside under overcast sky conditions*' [45]. Daylight Autonomy (DA) has been defined as '*the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone*' [47]. This study also used the maximum Daylight Autonomy (DAmax) [47] metric to evaluate possible glare problems in the daylit space; DAmax was defined as the percentage of time in one year when the illuminance at a sensor was at least ten times the design illuminance of a space. Therefore, a higher DA means a larger daylight availability while a higher DAmax indicates a bigger risk of visual discomfort and overheating. Useful Daylight Illuminance (UDI) was established to measure how often annual daylight illuminances within a range are achieved across indoor working planes [46]. UDI metrics have adopted several ranges to define various indoor daylight illuminances [46]: < 100 lx - too dark; > 3000 lx - too bright, and with high risk of glare and overheating; in the range 100–300 lx - be satisfactory either as the sole source of illumination or in conjunction with artificial lighting; furthermore, in the range 300 lx–3000 lx - be perceived either as desirable or at least tolerable. Definitely, a high UDI (100–3000 lx) value will be generally expected as a requirement for good daylighting practice. As percentages within different thresholds, these three UDI values meet the following relationship: UDI (< 100 lx) + UDI (100–3000 lx) + UDI (> 3000 lx) = 100%. In this study, nine typical positions (sensors) were analysed along the centre line of the room from the inner side of the façade to the back wall at 0.8 m above the floor, considered as the working plane – see Fig. 12. For each position, the DF, DA, DAmax, UDI (< 100 lx), UDI (100–3000 lx), and UDI (> 3000 lx) were calculated using the lighting simulation software Daysim. The required illuminance at the working plane for DA calculations was set at 500 lx [48,49]. The typical occupation pattern for the office room used in the simulations was from 8.00 a.m. to 5.00 p.m., which was set to justify the daylighting performance across the whole working day. The main ambient settings [44] used in the Daysim simulations for this study were: ad (ambient divisions) 2048, -ab (ambient bounces) 8, -as (ambient super-samples) 256, -ar (ambient resolutions) 124 and –aa (ambient accuracy) 0.1. The weather data of Madrid 082210 (IWEC) in Spain was used for daylighting simulation, which comes from a recognised database (energyplus.net/weather-location/

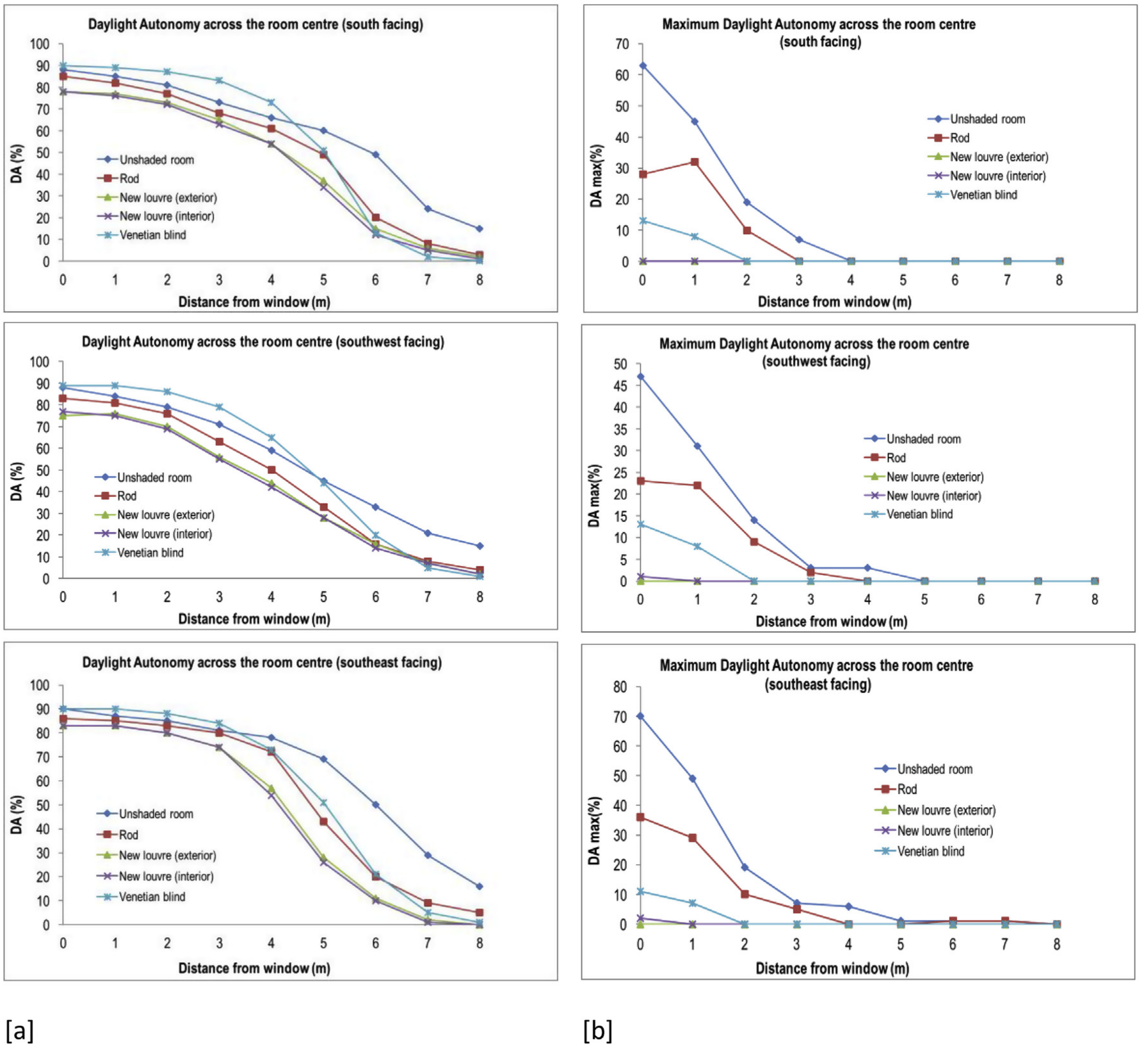


Fig. 14. Daylight Autonomy (DA) [a] and Maximum Daylight Autonomy) DAmax) [b] results for south, southeast and southwest orientations.

Table 2
Compared performance: aluminium venetian blinds vs. aluminium new louvre.

	DF (2–5%)	DA (%)						UDI (100–3000 lx) (%)								
		S		SE		SW		S			SE			SW		
		w	c	w	c	w	c	w	c	b	w	c	b	w	c	b
Venetian blinds	2.2–4.2 m	90	73	90	73	89	65	38	92	80	43	92	81	50	91	77
New louvre	0–4.2 m	78	54	83	57	77	44	84	81	67	88	87	75	81	87	63

Note: DF (Daylight Factor); DA (Daylighting Autonomy); UDI (Useful Daylight Illuminances); S (south orientation); SE (south east orientation); SW (south west orientation); w (by the window); c (centre of the room); b (back of the room). For the DA metric, values from the centre to the back of the room decrease towards 0.

europe_wmo_region_6). The data was produced by the meteorological station at Madrid based on the standards of the World Meteorological Organization.

4.2. Simulation results for specular louvres

Considering that the recommended illumination level for office work is typically 500 lx (DF 5%) [48,49], all the systems provided an adequately illuminated area (with a minimum accepted DF of 2% or above) for up to 4.2 m from the window; beyond that point all systems performed similarly, and the room would require electric light. The new louvre in both positions, exterior and interior, reached a comfortable DF range of 2–5% in all the areas upto 4.2 m from the window, providing the greatest adequately illuminated area, whereas the rest of the systems only reached that comfortable range in the area between 2.2 and 4.2 m from the window. The new louvres did not create the extremely high illuminance values near the window that can primarily be seen in the unshaded window case. Although this means a reduction of illuminance in that frontal area, it is good light for the required tasks. Furthermore, the uncovered window is not a viable solution anyway, given that the high illuminance near the window could make occupants close, partially or fully, a shading device, and that could dramatically reduce the level of illuminance in that area. Therefore, the new louvres successfully increased an even distribution of light levels across the room compared to the reference cases (Fig. 13).

Fig. 14 shows the DA and DAmax results obtained for the studied

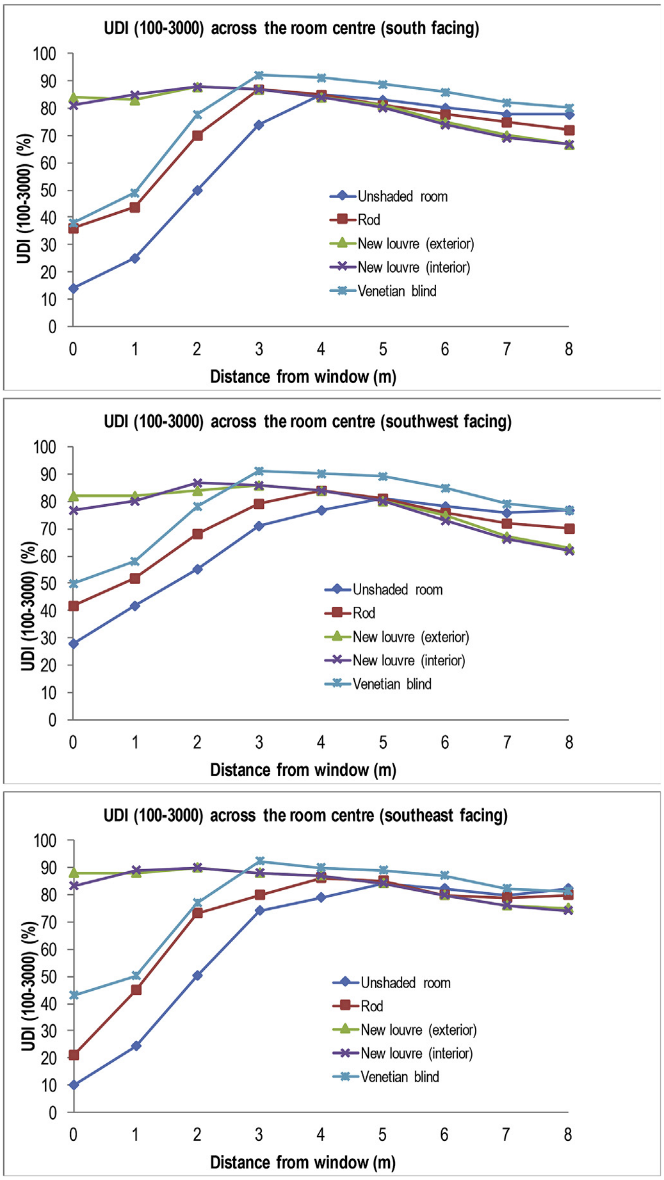


Fig. 15. Useful Daylight Illuminances (UDI) (100–3000 lx) for south, southwest and southeast orientations.

systems. The best performing system in the front half of the room (up to the first 4.2 m from the window), is the venetian blind, with the higher values in the south-east orientation (SE). In this area, the new louvres would be between 7% and 16% less efficient than the venetian blind in the SE orientation, which is also where they achieve their maximum value (Table 2). In the rear half of the room, the unshaded window presents the best performance, and the new louvre is between 1% and 28% less efficient than the unshaded window to bring light to this part of the space (also in the SE orientation). The new louvres achieve lower values than the rest of the systems, but the differences are small, with the external louvre providing slightly better values for all orientations. The venetian blind and the unshaded window provide more light across the room, in principle reducing the need for artificial lighting, but the new louvre distributed light more evenly, leading to better visual comfort. In this sense, the analysis of DAmax metric showed more favourable results for the new louvre. The values were significantly lower than the ones shown by the rest of the systems, with the external new louvre being the one offering the best results (DAmax 0%). This translates into a much-reduced period when potential glare conditions are present in the room. In comparison, the unshaded window shows very high DAmax values in the first half of the room (up to 70% in the SE orientation).

The values obtained for the useful daylight illuminance metric (100–3000 lx), confirm the even distribution of light and a satisfactory performance for the new louvre in the first half of the room, providing for the three orientations the highest percentage of the occupied times of the year when illuminances lie within this range (up to 88% in SE orientation). This successful performance progressively decreases towards the rear of the room, with its lowest value being 63% (SW orientation).

The venetian blind is a distant second close to the window, but its values dramatically improve towards the centre and second half of the room, where it presents results slightly better than the new louvre (10%, SE and SW orientations) (Fig. 15).

Fig. 16 shows the areas of the room and percentages of time in which the UDI results were too low or too high to be effectively comfortable. As expected, the rear of the room obtained the highest UDI (< 100 lx), slightly higher for the south west orientation, where the venetian blind presented values a little better than the new louvre.

Likewise, it was expected that the front of the room would get the highest UDI (> 3000 lx) values, in which the new louvre presented an excellent performance, especially if installed externally, reaching that threshold only in the first 2 m of the room in a very limited proportion (worst performance 0%–8% for SW orientation). The results for the venetian blind, the next best performing system, were far from protecting the front half of the room from this condition, presenting this situation up to 56% of the time (S orientation). The rods and the unshaded window showed a very poor performance, especially for the southeast orientation. Table 2 shows a summary of these results.

5. Assessing ceramics as a material for the new louvre system

5.1. Simulation settings

For this part of the study, the aluminium systems were replaced by louvres constructed of ceramic materials. For the daylight modelling of the Madrid office, all settings remained the same except for the change of materiality in the light-control devices, using two types of ceramic material finishes. Samples for these two ceramic finishes were produced at the laboratory of the Instituto Técnico Cerámico in Castellón, Spain: one with a standard glossy white glaze, and the other with a dark silver surface created with Physical Vapour Deposition (PVD) technology [50]. Fig. 17 shows the laboratory arrangement to determine the angular distribution of the reflectance around the specular peak of the ceramic samples. Their spectral reflectances were measured using the commercially available Lambda 900 UV/VIS/NIR Spectrometer of Perkin Elmer in Instituto de Óptica, Consejo Superior de Investigaciones Científicas, Madrid, Spain. Fig. 18 shows the measured spectral reflectance in the visible spectral range (380 nm–780 nm) of the white glossy ceramic and dark silver ceramic materials, considering the measurement modes: Specular Component Included (SCI) and Specular Component Excluded (SCE). It was found that the dark silver ceramic finish had a greater specular component than the white ceramic finish. The spectral properties of these materials have been included in the lighting simulations. Table 3 gives the photometric properties of room surfaces and shading materials. The overall reflectance of the shading materials were calculated based on their spectral reflectance, as shown in Table 3.

5.2. Simulation results

Starting with the recommended DF metric (2–5%), the two ceramic louvres met these values up to 2.2 m away from the window, with the external white ceramic louvre presenting slightly better results. The ceramic venetian blind performed a little better than the new louvre, meeting this range of values in a bigger area, up to 3.2 m from the

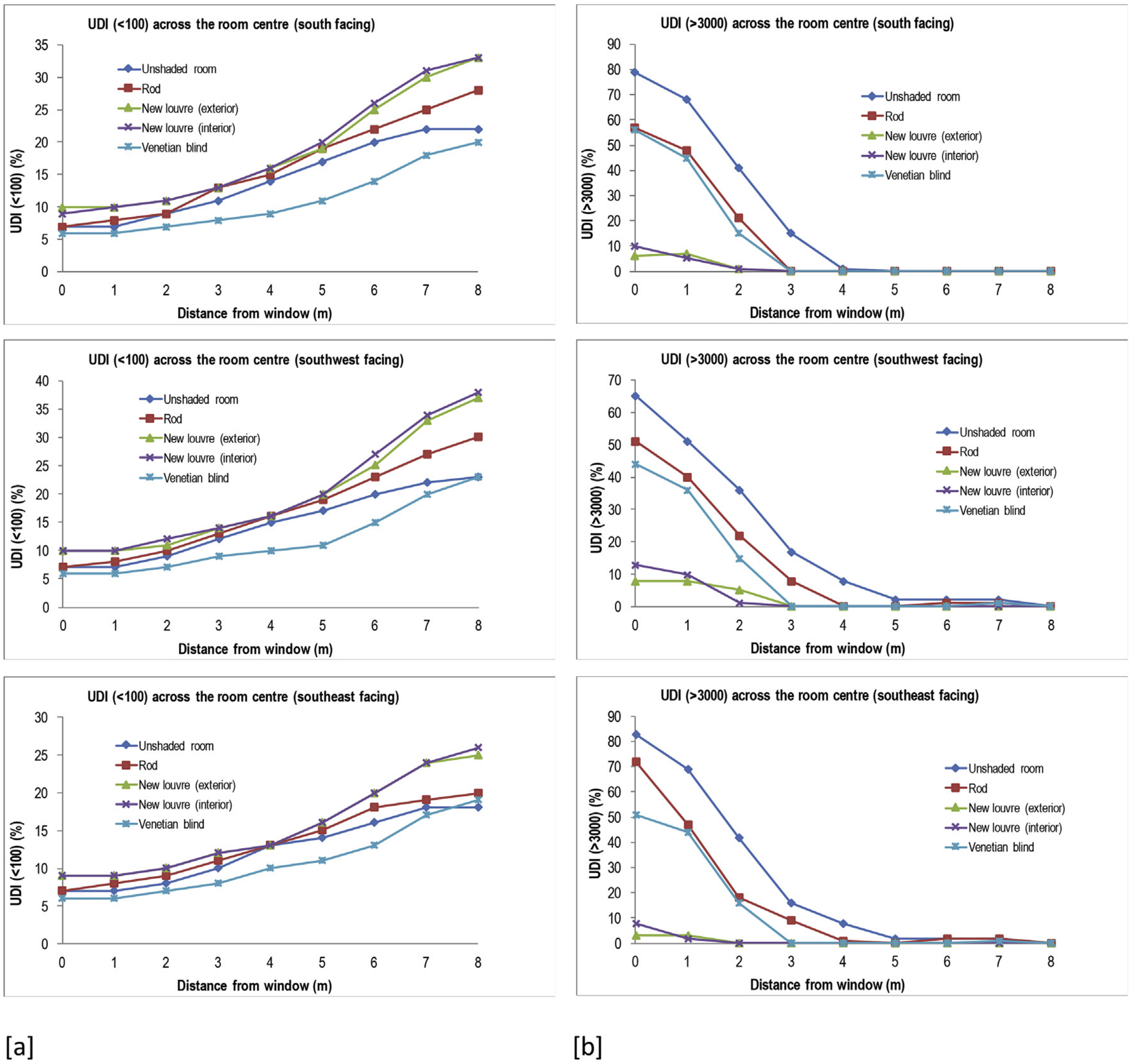


Fig. 16. Useful Daylight Illuminances (UDI) [a] (< 100 lx) and [b] (> 3000 lx) for south, southwest and southeast and orientations.

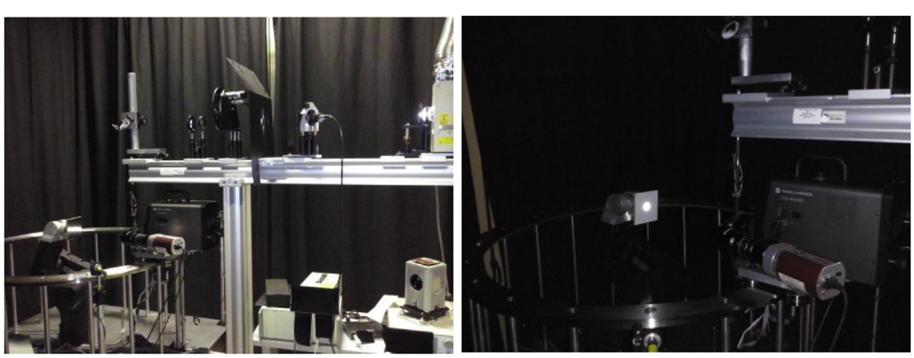


Fig. 17. Measurements of the spectral reflectance of the dark silver (left) and glossy white (right) ceramic samples, at Instituto de Óptica, CSIC.

window. The ceramic rod for both finishes provided an area equal to the new louvre, but in a different part of the room, between 2.2 and 4.2 m from the window, which also matched the results presented by the unshaded window. Beyond this distance, all the systems provide insufficient light, and the room would require artificial light in overcast sky conditions (Fig. 19).

In the first half of the room, out of the two ceramic louvres, the external white ceramic louvre provided the best performance, and the dark silver venetian blind provided a slightly better result than the white ceramic louvre, but this was only noticeable for the south west orientation (9–13% more efficient). The white ceramic rods and the unshaded window delivered slightly higher values than these systems: white rods reaching up to 90% (S orientation) and unshaded window reaching up to 90% (SE orientation), however, the analysis of the DAmax values revealed that the highest values for these two cases presented clear glare risks: up to 70% for the unshaded window, and up to 43% for the white ceramic rods, being the southeast orientation the most critical one. The two new ceramic louvres rarely reached this

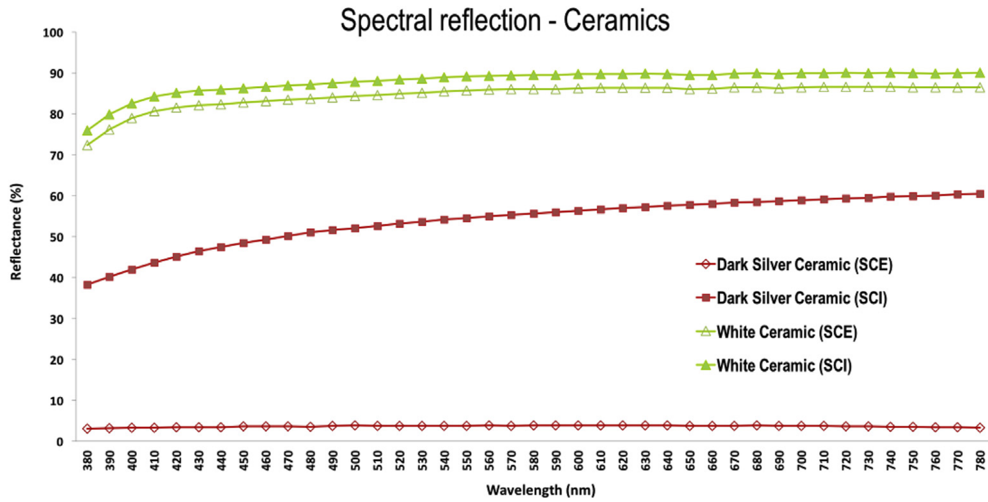


Fig. 18. Graph showing the spectral reflectance of the glossy white ceramic (top) and dark silver ceramic surfaces (bottom).

Table 3
Room and material surface photometric properties, and radiance descriptions.

Room Surface Photometric Properties	Reflectance/Transmittance
Wall	0.6 (grey, diffuse)
Ceiling	0.8 (white, diffuse)
Floor	0.3 (grey, diffuse)
Window	0.64 (double panes, transmittance), 0.8 (single pane, transmittance)
Shading Material Photometric Properties	**Overall Reflectance & Materials**
Ceramic rod	0.89 (white ceramics)
Ceramic rod	0.55 (dark silver ceramics)
New louvre (exterior)	0.89 (white ceramics)
New louvre (interior)	0.55 (dark silver ceramics)
Venetian blind	0.89 (white ceramics)
Venetian blind	0.55 (dark silver ceramics)
Shading Material	**Radiance descriptions**
White ceramics	mod plastic id 0 0 5 0.8956 0.8828 0.8505 0.0336 0.0000
Dark silver ceramics	mod plastic id 0 0 5 0.07866 0.07826 0.07204 0.51087 0.000
Polished aluminium	mod metal id 0 0 5 0.9138 0.9219 0.9246 1.000 0.000

threshold, obtaining a maximum value of 5% for the white louvre and 0% for the dark silver louvre (S orientation both); similarly, the white venetian blind reached a maximum value of 8% and the dark silver venetian blind reached a maximum value of 0%, both for south orientation (Figs. 20 and 21).

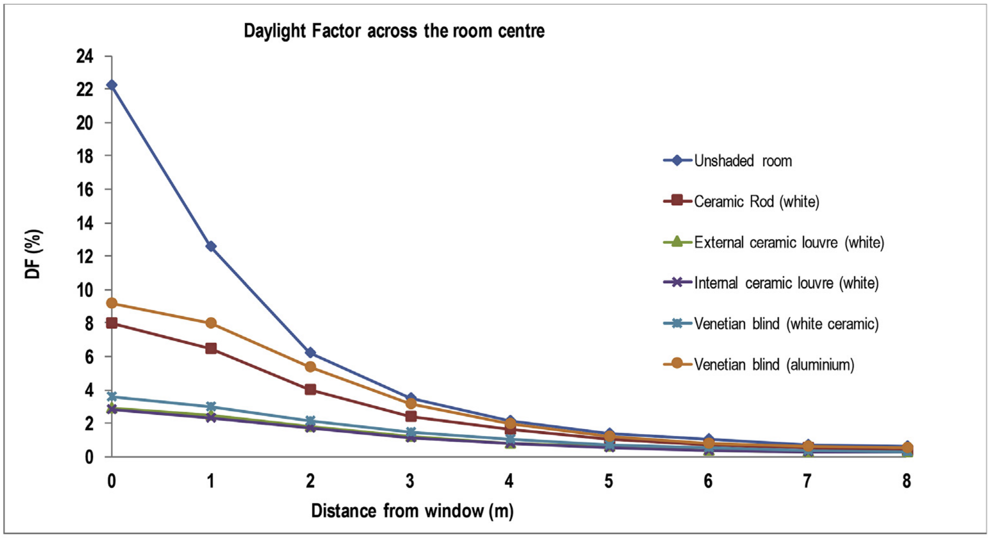
The results obtained for the UDI (100–3000 lx) metric were also favourable for the new ceramic louvres for the whole room: up to 91% (SE) for the white louvres, which showed a peak of performance in the centre of the room, and up to 92% (SE) for the dark silver louvre, which showed a better general performance. The closest following best performing system was the venetian blinds, reaching up to 90% (S) for the white venetian blinds. However, the dark silver venetian blinds performed slightly better than the dark silver louvre across the room, from window to back: reaching up to 92% in all orientations, which means that this system was between 2 and 24% more efficient, especially in the south west orientation (Figs. 22 and 23).

None of the ceramic louvres or venetian blinds reached the UDI (> 3000 lx) threshold. The white and dark silver ceramic rods and the unshaded window presented values too high to be comfortable, especially close to the window (66%, 46% and 79% respectively). As expected, the back of the room showed the lowest UDI values. The external white ceramic louvre performed better than the white venetian blind, as had happened previously. For the dark silver finish, the dark silver ceramic venetian blind was the best performing system, obtaining the best UDI (< 100 lx) values, closely followed by the white ceramic louvre (Figs. 24 and 25). A summary of these results can be seen in Table 4.

Assessing the values obtained for specular and ceramic finishes in the new louvre, the aluminium louvre outperformed the ceramic louvres for overcast skies (DF metrics) but had a similar or poorer performance for the DA and UDI metrics (Table 5). The white ceramic louvre outperformed the aluminium louvre for the DA and UDI (100–3000 lx) metrics, for south and south east orientations, and the dark silver ceramic louvre showed the best UDI (100–3000 lx) results for all orientations. In those cases where the aluminium louvre showed equal or better performance than the ceramic louvres (DF, DA southwest orientation), the ceramic louvres' achieved very close values, representing a very good solution in terms of performance and ecological impact.

In this study, it was deemed relevant to assess the change of material from aluminium to ceramics, in a well-established and widespread louvre system, such as venetian blinds. When comparing the aluminium venetian blinds with the ceramic venetian blinds, the following results were obtained:

- The aluminium blinds provided a greater area of adequate illuminance (with a minimum accepted DF of 2% or above) for up to 4.2 m from the window, but only the area between 2.2 m and 4.2 m from the window reached the comfortable DF range of 2–5%. The two ceramic blinds, white and dark silver, provided enough light up to 2.2 and 3.2 m from the window respectively, but beyond those points the room will require electric lighting. In both cases, all the space was illuminated within the comfortable lighting levels, so out of the three types of blinds, the dark silver blind actually provided a greater area of adequately lit space (3 m depth in to the room from the window).
- Looking at the DF metric for the two reference case studies, the unshaded window and the two types of ceramic rods achieved an acceptable DF up to the first 4.2 m and 3.5 m from the window



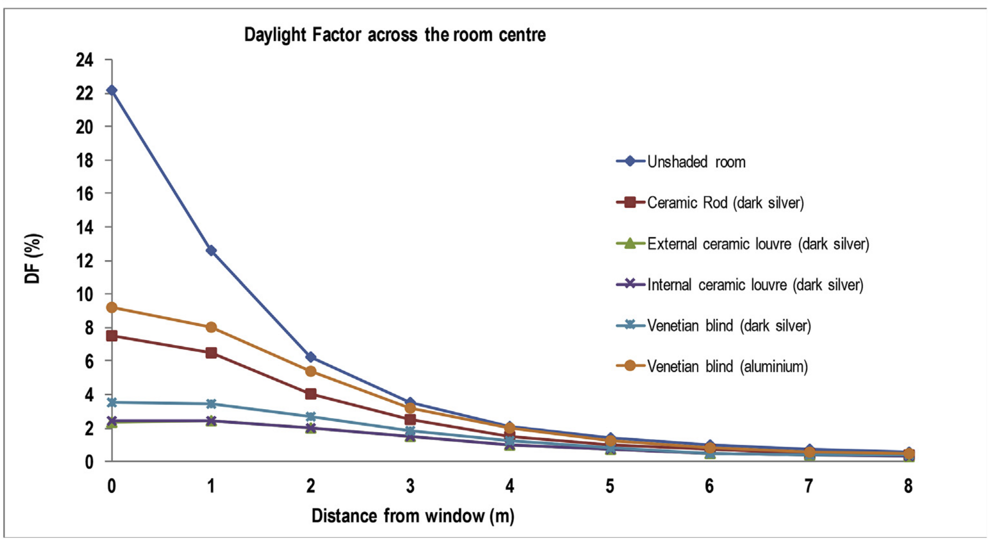
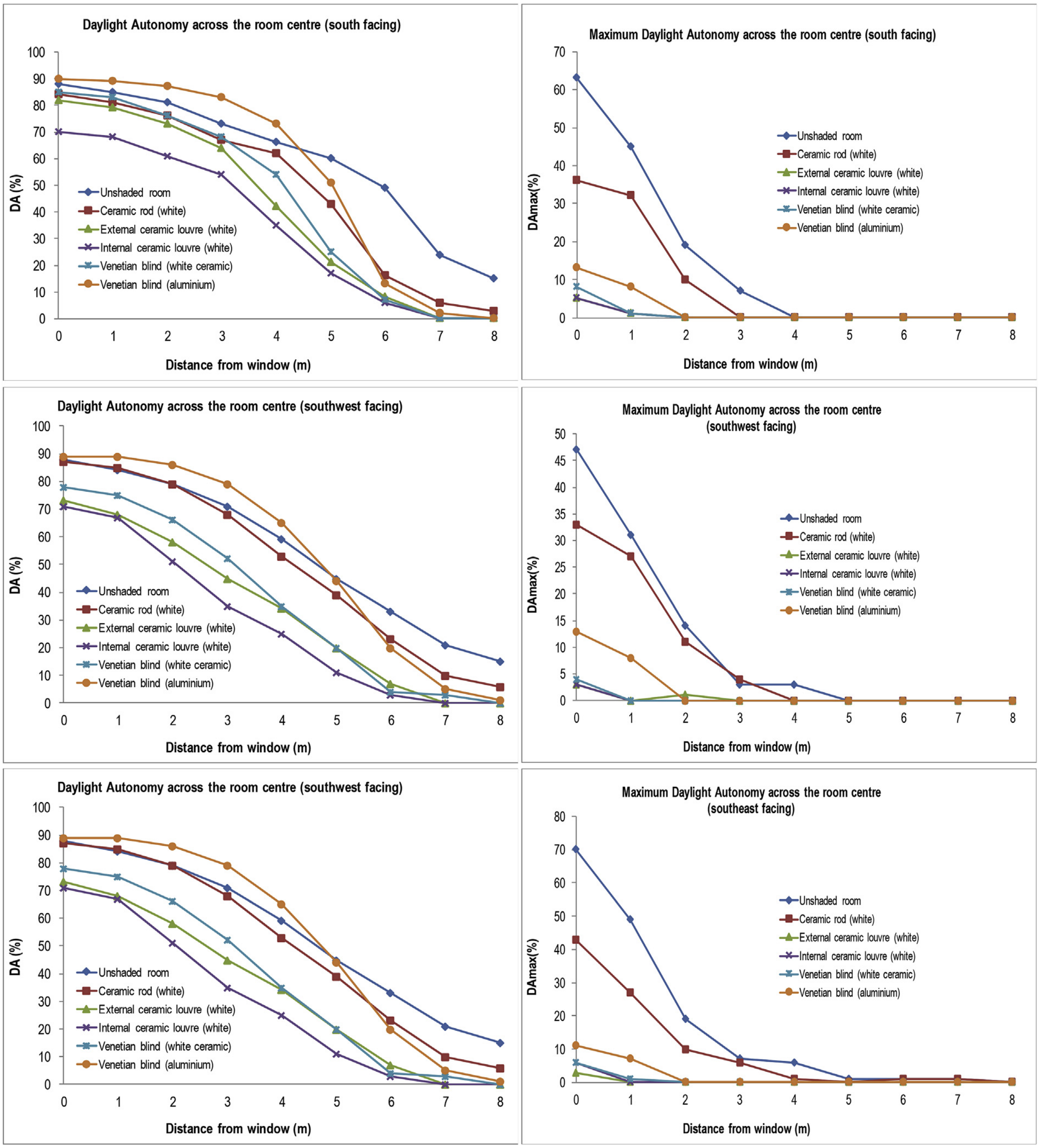


Fig. 19. Daylight Factor(DF) results for all compared systems for the glossy white ceramic finish (top) and the dark silver ceramic finish (bottom).

respectively, with ranges offering comfortable levels between 3 and 4 m for the unshaded window, and 1.5–3.5 m for the ceramic rods. Comparing these results to those obtained for the ceramic venetian blinds, the dark silver blind kept offering the best performance, providing a bigger area adequate illuminance area. In addition, the ceramic blinds did not create the extremely high illuminance values near the window that can be seen primarily in the unshaded window case. Therefore, the ceramic blinds successfully increased the even distribution of light levels across the room compared to the reference cases, as shown in Table 6.

- Looking at the daylighting autonomy data for the south orientation, the white ceramic blind achieved slightly lower values than the aluminium one up to the first 4.2 m, but it clearly presented a more limited performance for the deepest area of the room, and in the whole room for the other two orientations. The dark silver blind provided a weaker performance than the white blind for the south orientation but was better for the south-east and south-west orientations. However, it still generally performed worse than the aluminium blind. In the window half of the room, between 15 and 46%, 17%–50% and 22–65% of the year will require artificial lighting for each of the three orientations. For the same area close to the window, the dark silver blind would potentially require between 16 and 27% (S), 14–26% (SE) and 18–44% (SW) more electric lighting usage. In comparison, the aluminium blind reached slightly higher values, meaning that the room will need artificial illumination between 10 and 27%, 10–27% and 11–35% of the year for each orientation. Therefore, the aluminium blinds provided more light across the room, reducing the need for artificial lighting, but with the ceramic blinds daylight was more evenly distributed, leading to better visual comfort. In this sense, the analysis of the maximum daylighting autonomy metric showed much more favourable results for both ceramic blinds, since the values were significantly lower than for the aluminium blind, given that the dark silver blind offered the best results. This translates into a much-reduced period when potential glare or excessive lighting conditions were present in the room.

Examining the reference case studies, the daylighting autonomy of the unshaded window reached up to 90% in the front half of the room and up to 69% in the rear half of the room (SE orientation for both). The ceramic rod screen achieved daylighting autonomies of up to 91% (SE orientation) in the front of the room, and up to 62% (S orientation)at the rear of the room for the white finish; for the dark silver finish, it achieved up to 90% (SE orientation) at the front, and up to 69% (SE orientation) at the back of the room. Again, the first 4.2 m from the window offered the best results, meaning that the percentage of the year in which artificial light would be required reached up to 44% (S orientation) for the unshaded window, up to 33% (S orientation) for the



[a] [b]

Fig. 20. Daylight Autonomy (DA) [a] and Maximum Daylight Autonomy (DAmax) [b] results for south, southwest and southeast orientations, for the glossy white ceramic finish.

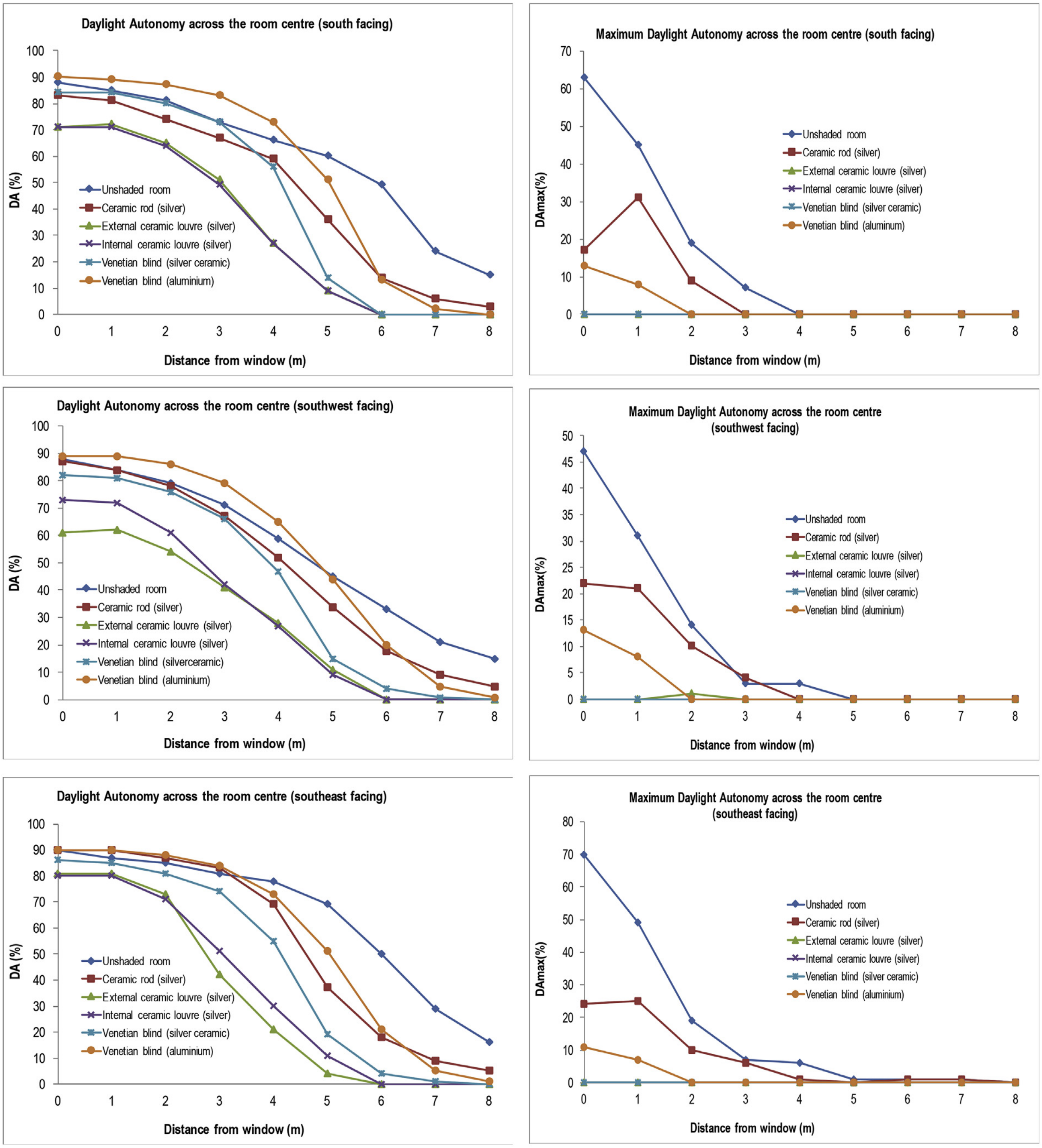
white ceramic rods, and up to 33% (S and SW orientations) for the dark silver ceramic rods.

In the front half of the room (3.5–4.2) metres, the aluminium blind shows the best performance, closely followed by the unshaded window and the dark silver ceramic blind (S); in the other two orientations, the ceramic rods had a slightly better performance than the dark silver blind.

The analysis of the maximum daylighting autonomy data still shows the best results for both ceramic blinds, since the values were significantly lower than for the reference case studies, with the dark silver blind offering the best performance and, therefore, the least opportunities for glare problems.

The values obtained for the UDI metric (100–3000 lx), also confirmed a satisfactory performance for the ceramic blinds, as shown in Table 4. The dark silver blind performed better than the white blind and the aluminium blind, especially for the first 3–4 m closer to the window, in which the white ceramic blind also outperformed the aluminium blind. The dark silver blind showed a better performance than any of the rods, closely followed by the white ceramic blind.

Figs. 14 and 15 show areas of the room and percentages of time in which the UDI results are too low or too high to be effectively comfortable. As expected, the rear of the room obtained the highest UDI (< 100 lx) values, slightly higher for the south west orientation: white blind (36%) and dark silver blind (28%). In this area, the ceramic blinds



[a] [b]

Fig. 21. Daylight Autonomy (DA) [a] and Maximum Daylight Autonomy (DAmax) [b] results for south, southwest and southeast orientations, for the dark silver ceramic finish.

performed a little worse than the unshaded window and the aluminium blind (white blind), or than the unshaded window, aluminium blind and ceramic rod (dark silver blind). Likewise, it was expected that the front of the room would get the highest UDI (> 3000 lx) values, in which the dark silver ceramic blind showed an excellent performance, since it did not reach that threshold for any orientation, while the white ceramic blind remained much lower (the maximum value achieved was 29% for south-east orientation) than the rest of the studied systems.

6. Conclusions

A new daylighting screen based on hollow louvre profiles has been evaluated using computer simulations. In most of the cases, the louvre placed externally showed better results than the louvre placed internally. For all metrics, the new proposed external louvre greatly outperformed the rod, which is the current standard applied profile for solar screens using hollow components; the use of hollow profiles was considered necessary for implementing potential thermal control benefits through evaporative cooling or phase change materials.

As a specular system, the new ceramic louvre outperformed all the modelled systems for overcast skies. For sunny situations, the new louvre was less successful at increasing lighting levels in the room than the rest of the studied systems, as the DA metrics show, but its performance was not far from the best performing system, the venetian

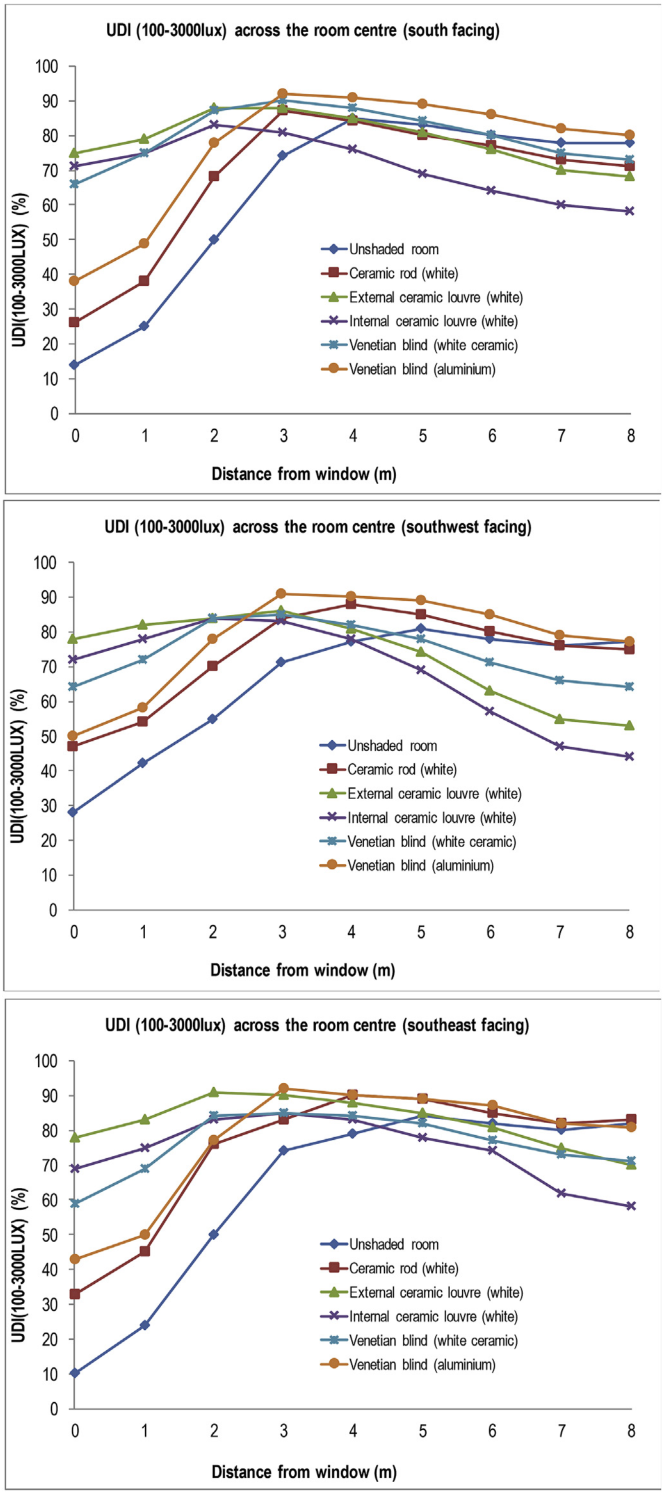


Fig. 22. Useful Daylight Illuminances (UDI) (100–3000 lx) for south, southwest and southeast orientations, for glossy white ceramic finish.

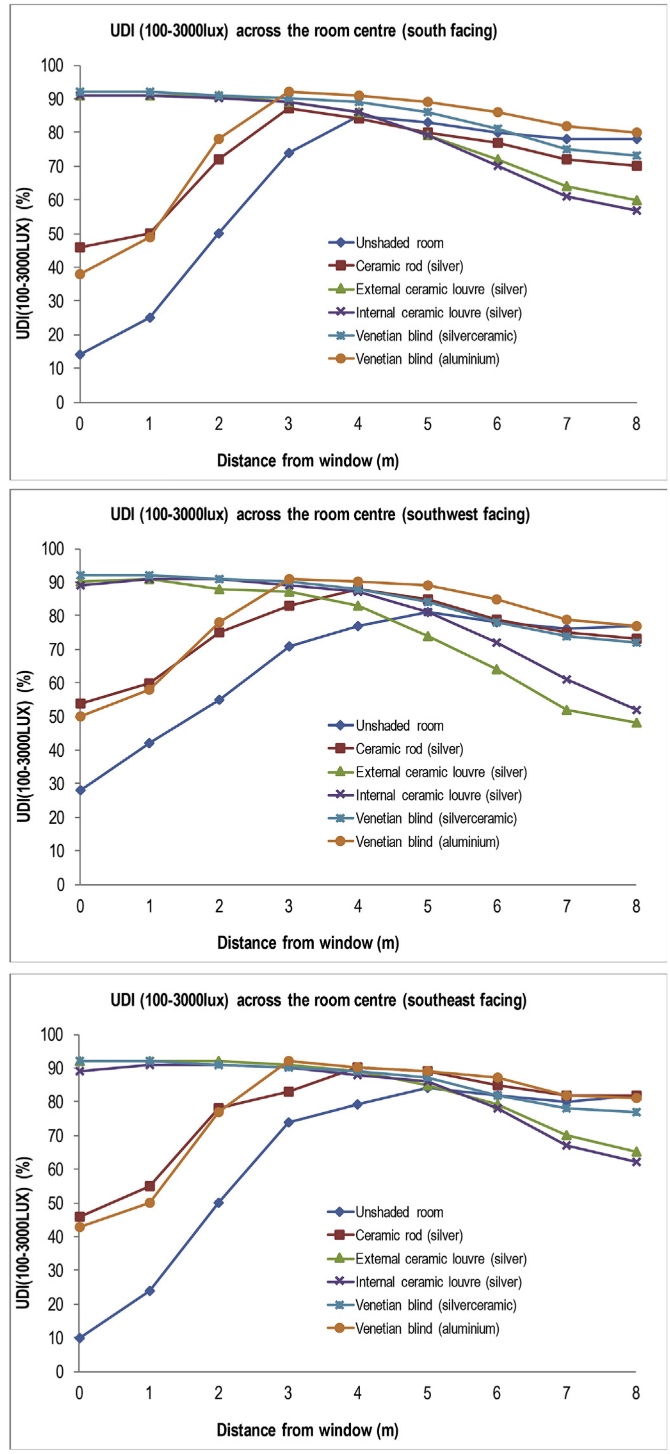
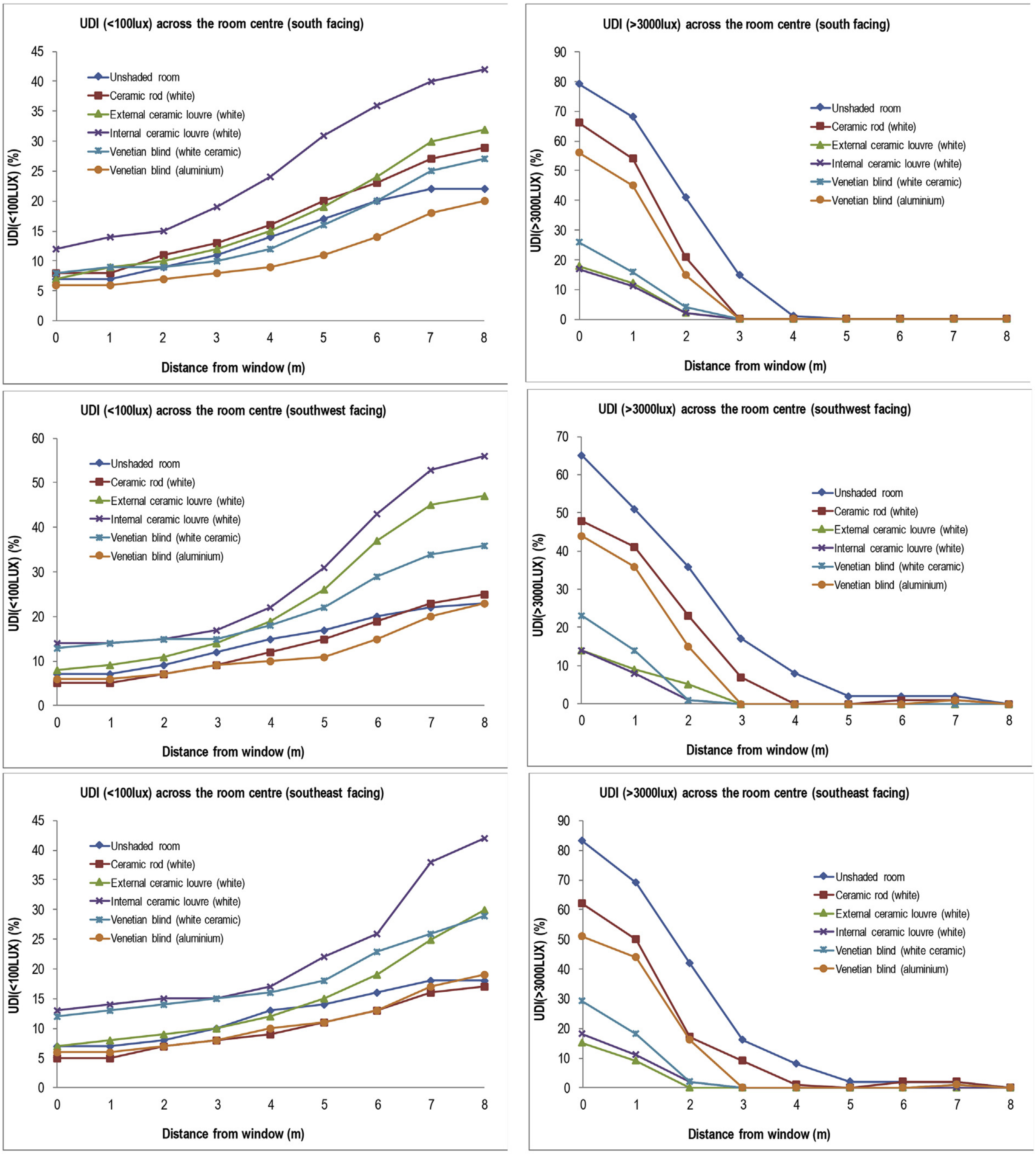


Fig. 23. Useful Daylight Illuminances ((UDI) 100–3000 lx) for south, southwest and southeast orientations, for dark silver ceramic finish.

blind, and it was the most successful at distributing light evenly and reducing risk of glare, as shown by the DAmax and UDI metrics.

The feasibility of the use of ceramics for louvre systems for sunlight control and daylight distribution has also been evaluated using computer simulations for two different finishes. As a ceramic system, which would improve the ecological footprint of the louvre production, the new louvre showed a very positive performance, especially for sunny situations, which is the most common condition in the modelled region (Madrid): in all these situations, the ceramic option performed equal to or better than its aluminium version. When compared to the ceramic venetian blinds, the external white ceramic louvre provided equal DA performance as the dark silver venetian blind, which is only slightly lower for the south west orientation, being these two the best performing systems. In terms of UDI in the comfortable range of values (100–3000 lx), the dark silver venetian blind performed slightly better than the dark silver louvre across the room, especially for the south west orientation.

In all the modelled cases, the proposed ceramic louvres performed



[a] [b]

Fig. 24. Useful Daylight Illuminances (UDI) [a] (< 100 lx) and [b] (> 3000 lx) for south, southwest and southeast orientations, for glossy white ceramic finish.

better than the rest of systems at providing a more even lighting distribution within the lit area, which offers the best option to achieve visual comfort, minimising the potential for glare episodes. This first analysis showed that the ceramic louvre system would create an even daylight illuminance distribution for both overcast and clear skies, which indicates a reduced risk of visual discomfort because of the lower contrast between window and the rear of the room. Most of the assessment between systems has focused on the area closer to the window (up to the first 4.2 m), since from that distance onwards all the systems delivered unsatisfactory lighting levels, and therefore did not boost enough light at the back of the room. In that sense, all these systems have a more significant role as to even out the lighting levels and prevent glare in that area, and the new profile, together with the use of ceramics, provided the best response to this task, especially the one with the dark silver finish, as the DF, DAmax and UDI metrics proved.

In terms of artificial lighting energy savings, the aluminium venetian blind provided the best performance, delivering up to 30% (SW orientation) more daylighting autonomy than the white venetian blind, and offering potential electricity savings of up to 30% (SW) when compared to this blind, but only of up to 7% (SW orientation) more daylighting autonomy and potential to save in electrical lighting than the dark silver venetian blind. The results from this metric place the dark silver venetian blind in a very good position as an alternative to the aluminium venetian blind.

Both ceramic louvres and venetian blinds present a DA above 50% for half of the room (up to the first 4.2 m) for south and south-east

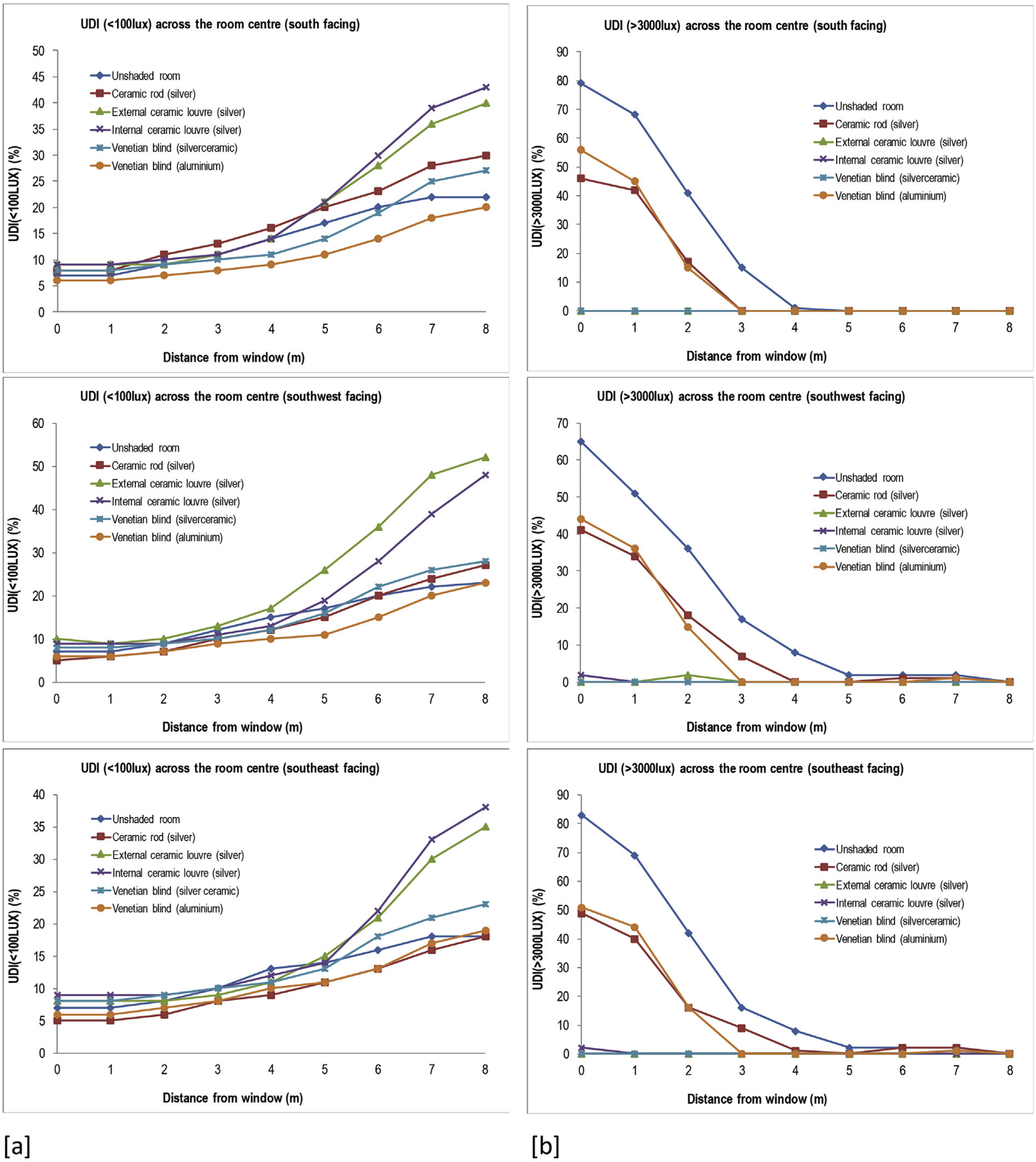


Fig. 25. Useful Daylight Illuminances (UDI) [a] (< 100 lx) and [b] (> 3000 lx) for south, southwest and southeast orientations, for dark silver ceramic finish.

Table 4
Compared performance: ceramic venetian blinds vs. ceramic new louvre (exterior).

	DF (2–5%)	DA (%)						UDI (100–3000 LX) (%)								
		S		SE		SW		S			SE			SW		
		w	c	w	c	w	c	w	c	b	w	c	b	w	c	b
White venetian blind	0–2.2 m	85	54	83	50	78	35	66	90	73	59	85	71	64	85	64
Dark silver venetian blind	0–3.2 m	84	73	86	74	82	66	92	90	73	92	90	77	92	90	72
White new louvre	0–2.2 m	82	42	86	42	73	34	75	88	68	78	96	70	78	86	53
Dark silver new louvre	0–2.2 m	71	27	81	21	61	28	91	85	60	92	88	65	90	82	48

Note: DF (Daylight Factor); DA (Daylighting Autonomy); UDI (Useful Daylight Illuminances); S (south orientation); SE (south east orientation); SW (south west orientation); w (by the window); c (centre of the room); b (back of the room). For the DA metric, values from the centre to the back of the room decrease towards 0.

Table 5
Performance of the new louvres: aluminium vs. ceramic finishes (exterior).

New louvre	DF (2–5%)	DA (%)						UDI (100–3000 LX) (%)								
		S		SE		SW		S			SE			SW		
		w	c	w	c	w	c	w	c	b	w	c	b	w	c	b
Aluminium	0–4.2 m	78	54	83	57	77	44	84	81	67	88	87	75	81	87	63
White ceramics	0–2.2 m	82	42	86	42	73	34	75	88	68	78	96	70	78	86	53
Dark silver ceramics	0–2.2 m	71	27	81	21	61	28	91	85	60	92	88	65	90	82	48

Note: DF (Daylight Factor); DA (Daylighting Autonomy); UDI (Useful Daylight Illuminances); S (south orientation); SE (south east orientation); SW (south west orientation); w (by the window); c (centre of the room); b (back of the room). For the DA metric, values from the centre to the back of the room decrease towards 0.

Table 6
Performance of venetian blinds: aluminium vs. ceramic finishes.

Venetian blinds	DF (2–5%)	DA (%)						UDI (100–3000 LX) (%)								
		S		SE		SW		S			SE			SW		
		w	c	w	c	w	c	w	c	b	w	c	b	w	c	b
Aluminium	0–4.2 m	90	73	90	73	89	65	38	92	80	43	92	81	50	91	77
White ceramics	0–2.2 m	85	54	83	50	78	35	66	90	73	59	85	71	64	85	64
Dark silver ceramics	0–3.2 m	84	73	86	74	82	66	92	90	73	92	90	77	92	90	72

Note: DF (Daylight Factor); DA (Daylighting Autonomy); UDI (Useful Daylight Illuminances); S (south orientation); SE (south east orientation); SW (south west orientation); w (by the window); c (centre of the room); b (back of the room). For the DA metric, values from the centre to the back of the room decrease towards 0.

orientations, and a little lower for the south-west orientation (up to the first 3.2 m). As a side-lit room was being considered, the DA was expected to vary with façade orientation and the choice of working hours modelled, producing the higher values for south and south-east orientations. Obviously, achieving an illuminance of 500 lx for this long period (8.00am–5.00pm) in the whole room is a very challenging target for any daylighting technology. According to some studies and codes, achieving between 300 and 500 lx is considered adequate for office spaces, and that would significantly increase the efficiently lit area to more than half of the room [51,52].

The dark silver ceramic louvres present excellent UDI (100–3000 lx) results, followed by the dark silver ceramic venetian blind, when considering the requirement to meet this value 80% of the time, which happened for nearly the whole room. For the white ceramic louvres, the UDI (100–3000 lx) performance was more limited, with only the central part of the room reaching the 80% threshold.

Window design is a key factor in daylight control. As it is known, larger openings generate higher UDI (< 100 lx), but to the detriment of achieving a good UDI (100–3000 lx) value. If DF is only considered, it will encourage the use of large expanses of glass, and the need to control overheating or glare will need to be addressed. These UDI results evidenced how to optimise the daylight distribution through window design, in terms of size, shading strategies (i.e. overhangs), number of windows and their location around the room in order to improve an even distribution of light. Another factor to take into consideration is that sunnier locations result in higher UDI (< 100 lx) values. Thus, further investigations on the feasibility of using the new louvre and ceramics for daylight control would require modelling for different window design alternatives and different geographic locations.

The results from this preliminary study are very encouraging regarding the effectiveness of introducing ceramic finishes to daylighting systems. However, to validate these results more investigations of performance (sunlight control, visual comfort and daylighting efficiency) need to be done for other daylighting systems and contexts. Once the optical performance of these two ceramic finishes are now measured and understood, the design of existing systems whose design is based on a mostly specular interaction with light can be revisited and adjusted to these material properties, to achieve an optimised performance. Likewise, new daylighting systems can be developed based on these photometric properties, and we are currently working towards this goal.

This study is the first step in a programme of work to investigate a combined performance of ceramics that tackles visual and thermal comfort and energy optimisation. The possible environment applications of ceramics are still relatively untested architecturally. However, the potential benefits of integrating such a low impact material into a sustainable building design can only increase as the operating energy used to service buildings becomes proportionally smaller in the future because of more demanding building energy regulations.

Declarations of interest

None.

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